SOME ASPECTS OF THE MECHANICS OF PIANO PLAYING

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SYNOPSIS

The chief purpose of this thesis is to make a thorough examination of the leading works written on the technique of piano playing. The theories expounded in these works tend to be based on rather unscientific methods of analysis. The first object of the thesis is therefore to attempt to put the whole subject on a more scientific basis. In doing so, use is made of computer simulation methods, possibly for the first time in this field. In discussing the action of the piano, the old controversy over tone-quality is raised. New techniques for playing the piano are proposed. A scheme for more efficient learning, using electronic instrumentation, is proposed. Comments are made on the desirability or undesirability of introducing changes to the basic action of the piano.

Part of the thesis (the section on arm movements) has been deliberately kept free of references to piano playing, so that it may be of general biomechanical interest.

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INTRODUCTION : STATE OF THE ART

It is the purpose of this thesis to examine scientifically the mechanical processes involved in playing the piano. Before carrying out such an investigation, it is necessary to study the existing literature. Many books have appeared on the subject of piano playing, but the majority of them are written at a comparatively elementary level. The most important books written this century in English at an advanced level seem to be the following (which are arranged chronologically):-

BRÉE (1902, pp.121). This book is well illustrated, containing many photographs of hands playing the piano. In it, Madame Bree writes an account of the methods of the celebrated teacher Theodore Leschetizky, who gives his approval to the book. One wonders, though, how much is Leschetizky and how much is Bree.

MATTHAY (1903, pp.328). Matthay starts from scratch and builds up his own entirely original methods of piano playing, using a fairly rigorous analytical approach. He is critical of all previous writers.

BREITHAUPT (1909, pp.100). Breithaupt's methods are derived from those of the German school of piano playing evolved by Deppe and others. His first book was written in 1904, and does not seem to have been translated from the German. His 1909 book is a condensed version of the earlier work and exists in translation. As in Bree's book, there are many illustrations.

ORTMANN (Vol.1, 1925, pp.189; Vol.2, 1929, pp.395). Volume 2 covers the same ground as the earlier books in this list. Volume 1, however, is devoted entirely to the qualitative properties of sound produced by the piano. A projected third volume on the psychology of piano playing was never completed. Ortmann's two books are probably the first works on piano playing to use proper scientific method, and resulted in Ortmann being branded as an enfant terrible.

FIELDEN (1927, pp.177). Fielden carries out his investigations in much the same way as Matthay, and in fact examines Matthay's work closely, but comes to different conclusions.

MATTHAY (1932, pp.235). In this book, Matthay condenses and clarifies his previous writings. He also replies to criticisms of his earlier work.

CHING (1934, pp.117). Ching, probably the most scientific of all the investigators, carries on the work of Ortmann and Fielden and adds new methods of his own.

SCHULTZ (1936, pp.317). Schultz carries out his own extensive investigations into piano playing in a partly scientific manner. His book includes a long review of the work of Bree, Matthay (1903), Breithaupt and Ortmann.

CHING (1946, pp.356). This is an improved version of the 1934 work, containing some of Schultz's ideas.

BONPENSIERE (1953, pp.128). This book is quite intriguing and is radically different from all the others. Bonpensiere's advice is to forget all about mechanical theories and instead teach the brain to develop its technique by instinct.

HARRISON (1953, pp.77). This is a short, straightforward book which steers a middle course amongst the theories of previous writers. Harrison does not set out to prove anything new.

GAT (1958, pp.228). This book (translated from the Hungarian) is written in a similar fashion to Bree's and Breithaupt's works. It is copiously illustrated and contains sequences of "stills" from films of famous pianists performing.

In this thesis, these books are examined, using scientific methods and taking advantage of recently published biomechanical data. Perhaps for the first time, computer techniques are employed in this field. A further aim of the thesis is to make some general biomechanical observations.

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THE MECHANICAL REQUIREMENTS OF PIANO PLAYING

1.0 INTRODUCTION

This chapter lays a basis for the whole thesis. Firstly, the general requirements of piano playing are set out. Secondly, scientific definitions are given to the musical terms which are used in this thesis. The chief purpose of Chapter 1 is to translate musical ideas into scientific ones so that the rest of the work can proceed scientifically.

The sort of piano playing studied in this thesis is that needed to perform the works of the great composers. Other forms of piano playing, e.g. improvisation, have less stringent requirements.

The musical ideas in this chapter represent the general consensus of opinion and are drawn from a wide variety of sources, namely books, periodicals, newspapers, gramophone records, and radio and television programmes in the form of performances, discussions and criticisms. Only a few references have been specifically named.

A glossary of musical terms is given in Appendix 3.

1.1 PIANO PLAYING : A BROAD VIEW

A pianist faces two problems : firstly he must form a very clear idea of the sounds he wants to draw from his instrument; secondly he must use his hands to produce those sounds. To solve the first problem he needs aesthetic understanding; to solve the second problem, he needs technical ability. It is this technical ability, or "technique", that forms the subject matter of this thesis.

In fact piano technique covers a wide field. To begin with, the brain must decide which notes are to be played, what their degree of loudness will be, and exactly where they will occur in time. This initial decision depends on information stored in the brain as a result of both deliberate "memorisation" and of past experience. Furthermore, this information must be retrieved very quickly (actually whilst one is playing). Therefore the first requirement of a good piano technique is to have an efficient memory.

Secondly, when the brain has made its decision, it has to send out appropriate signals to the muscles of the upper limb. These too depend on stored information, partly due to an intellectual grasp of the mechanical properties of the arm and piano, and partly due to long-term adaptive processes aimed at acquiring "skill". These signals must pass from brain to muscle via the nervous system. A second requirement of piano technique, therefore, is to have a good nervous system capable of producing steady muscular control and rapid reflex actions.

When the signals reach the muscles, the muscles must perform the required action, and the various sections of the arm must move accordingly. Clearly, then, a third requirement is to have a good quality, athletic arm; that is, one with strong muscles, good joints, and freedom from superfluous tissue.

A bad workman blames his tools; bad pianists usually blame their piano. All the same, one is very much at the mercy of the piano when it comes to producing music. A fourth requirement of good piano playing is to have a good piano.

When the sounds have been produced from the piano, the pianist must analyse them carefully. If they are unsatisfactory (they usually are), he must decide exactly what is wrong. His top priority (in a public performance) is to adjust his interpretation of the piece he is playing in order to compensate any error as much as possible. Having done this, he must analyse whether his arm actions are at fault and make any necessary changes. (This is part of the long-term adaptive process mentioned earlier). Thus, a fifth requirement of piano technique is to have a well-trained ear, masses of experience of differing acoustics, and a highly-developed faculty for self-criticism.

For a concert pianist, there is a sixth requirement. This is that he must be able to achieve the right state of mind for public performance. Any nervousness immediately sabotages the decision-making part of the brain, and the resulting poor playing gives a positive feedback situation, with unfortunate results.

Technique, then, covers a wide field, from various aspects of psychology, through neurophysics and biomechanics to mechanics and the theory of sound. There is material here for dozens of Ph.D. theses. At present, the field seems to be wide open (see

Appendix 4). The area chosen for study in this thesis is that which begins where the muscles receive their signals from the nervous system and ends where sounds are produced from the piano. Thus, we shall be concerned with the mechanical properties of muscles, with the inertia of the skeleton, with the mechanical action of the piano and with the nature of the resulting sounds. Much of the analysis of arm movements has been kept free of reference to piano playing, so that it may be of more general interest.

1.2 THE PIANOFORTE (Taylor (1965), Grove, Olson (1952))

The grand piano in its modern form was developed between the middle of the eighteenth and the middle of the nineteenth centuries. The keyboard consists of 88 keys, 52 white and 36 black, arranged in a repeating pattern of twelve as shown in Fig.1.2.1. Each white key is 2.3 cm. wide and has an exposed length of 15 cm. Each black key is 1.0 cm. wide and has an exposed length of 10 cm. The surface of the black keys is 1.0 cm. above that of the white. The keys may be depressed individually (with no restrictions on simultaneity) through a distance of 1 cm. (at the front edge) at which they come into contact with the keybed, which is fitted with felt pads to prevent sharp impact of the keys. When all force is removed from a key, it returns to its normal position by gravity.

When each key is depressed, a mechanism causes a small felt-covered wooden hammer to strike a set of strings (one string per hammer for low pitches, two for medium pitches, and

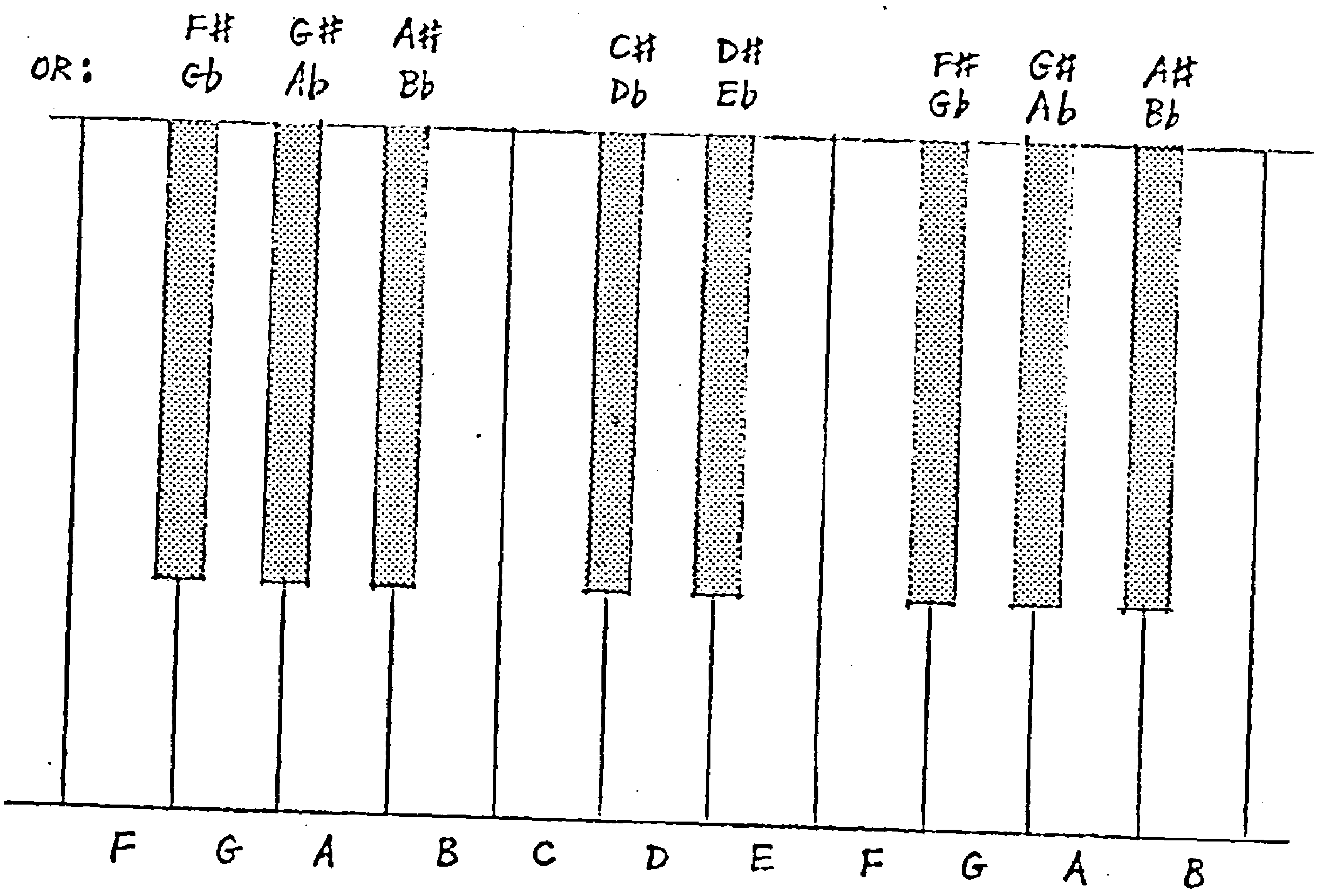


Fig. 1.2.1. A piano keyboard

The letters indicate the names of the pitch of each note.

three for high pitches). The tensions of the strings are fixed permanently, so that each key has a definite pitch associated with it, as shown in Fig.1.2.1. These pitches are worked out on the system of equal temperament. (Sec.1.10)

The vibrations of the strings are picked up (by sympathetic vibration) by a wooden sounding-board which lies beneath them, and by this means the sound is amplified so that it can be heard clearly.

The minimum force needed to depress the key of a Broadwood piano (which is quite typical) is given, with dates, as follows (Grove) :-

	Lowest C	Middle C	Highest C
1817	$2\frac{5}{8}$ ounces	$2\frac{3}{8}$	$1\frac{3}{4}$
1877	4	$3\frac{1}{8}$	$2\frac{3}{8}$
1904	3	$2\frac{1}{2}$	2

("Middle C" is that note "C" which lies nearest the centre of the piano.) The black keys are compensated so that they have the same inertia as the white keys.

Each set of strings is fitted with a damper to prevent the strings from vibrating until they are struck. When a key is depressed, its damper is automatically lifted to enable the note to sound. The damper is replaced when the key is released. All the dampers can be controlled en bloc by a pedal operated mechanism (often called the "sustaining pedal"). When the pedal is depressed, all the dampers are lifted. This has two effects. Firstly, each note which has been struck carries on sounding whether the key is released or not, and secondly, the sound of each struck note is slightly different in quality because of the sympathetic vibration of the other strings.

There is a second pedal on the piano (sometimes called the "soft pedal") which moves the entire keyboard slightly to the right, so that the hammers of the higher pitched strings leave at least one string in each set unstruck. This produces a different quality of sound again.

Of course, when a key is depressed, the resulting sound is not indefinitely prolonged, but dies away exponentially. The decay of the sound naturally depends very much on the acoustic conditions.

1.3 MUSICAL STRUCTURE : DEFINITIONS

Some space will now be devoted to a study of musical structure to show what a pianist playing the works of the great composers is expected to do. The next six sections cover musical structure as it affects the pianist, beginning with an examination of the various ways of connecting notes in a sequence, and going on to look at the kinds of structures used by each of the great composers, with examples of extreme cases taken from the musical literature. Firstly, however, it is necessary to define "musical structure".

The term "musical structure" can have various meanings, depending on context. Firstly, it can refer to the relationship between the different pitches in existence at a given instant during a piece of music. In this case it is also known as "harmonic structure". Secondly, "musical structure" can refer to the organisation of sequences of notes throughout the whole of the musical composition. This is also known as "thematic structure". Thirdly, "musical structure" can refer to the patterns of notes which are to be played, regardless of their musical effect. In this case, each pattern can be regarded purely and simply as a technical problem.

Of course, these three meanings are only different aspects of the same thing, but it is important to distinguish between them. In this thesis, the term "structure" will always have the third of these meanings.

1.4 MUSICAL STRUCTURE : FINE SCALE (CONNECTIVITY)

All music is built up from sequences of notes, so an examination of musical structure should logically begin by considering the relationship between just two notes, played consecutively. Take, for example, the note B followed by the note C (Fig.1.4.1). The times at which the notes are struck are indicated fairly precisely by the musical notation. Thus, for example, if the basic speed is 60 crotchets per minute, then a graph of the resulting sound against time would look something like Fig. 1.4.2. (This is assuming the notes to be played on a piano - hence the exponential decay). What the musical notation does not indicate is the point in time at which each note should cease to sound. Now there is a convention that, unless the score indicates otherwise, one note should take up where the other leaves off - in our example, the "B" should be suppressed at the instant the "C" sounds. (Fig.1.4.3) This type of connection is referred to as "legato". In practice, however, the convention is rarely adhered to strictly. Nineteenth century music, being written for a piano-

Fig 1.4.1

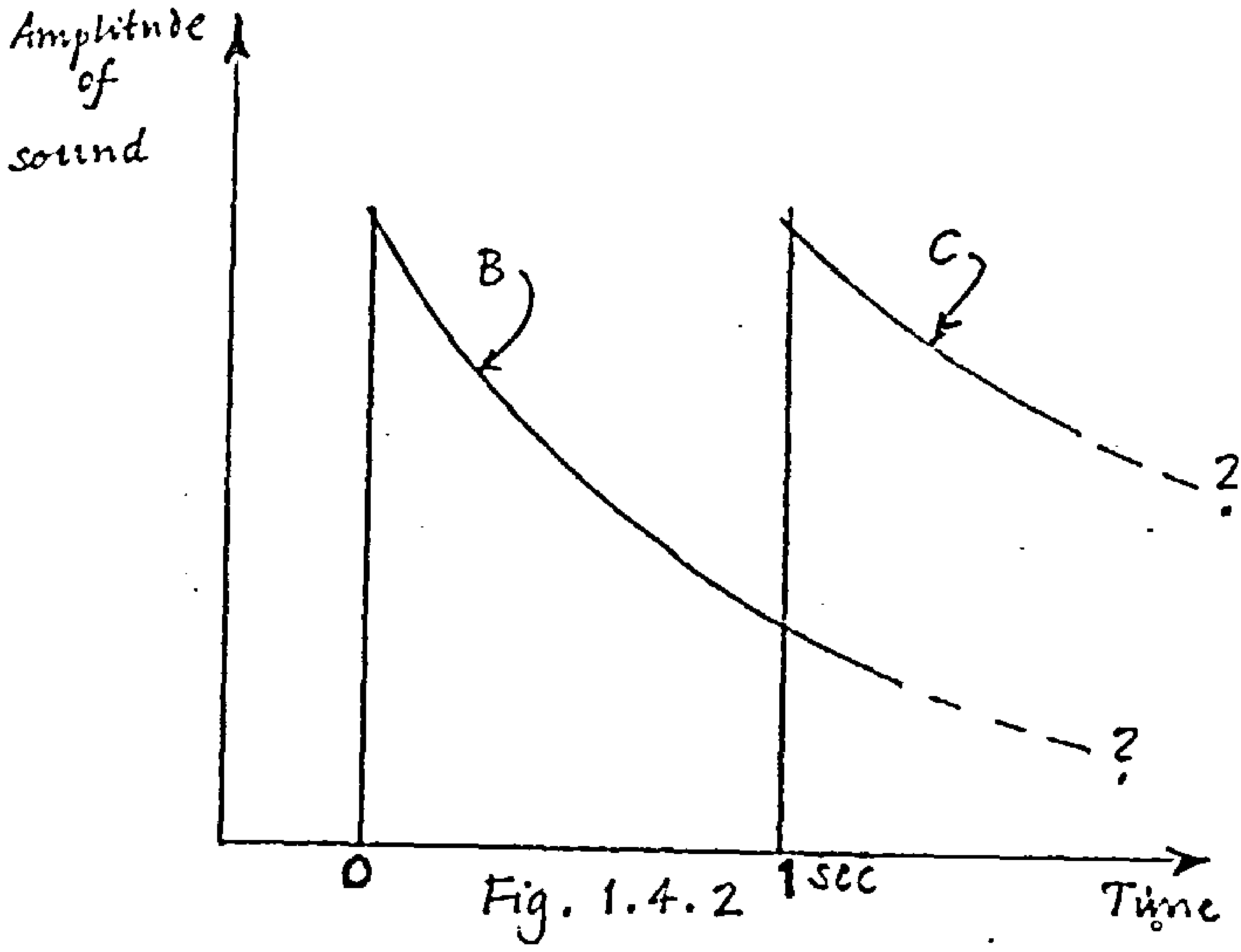


Fig. 1.4.2

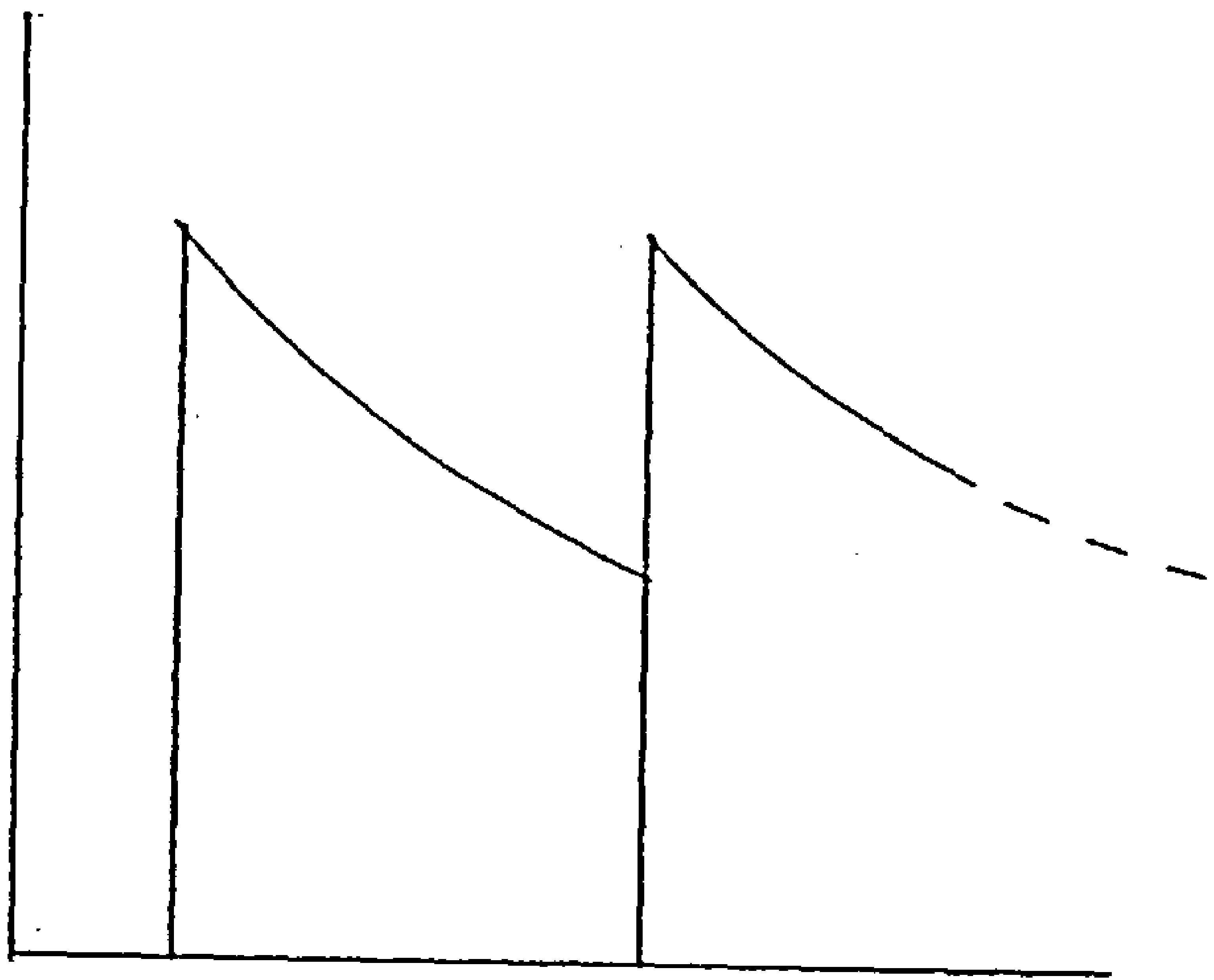


Fig. 1.4.3

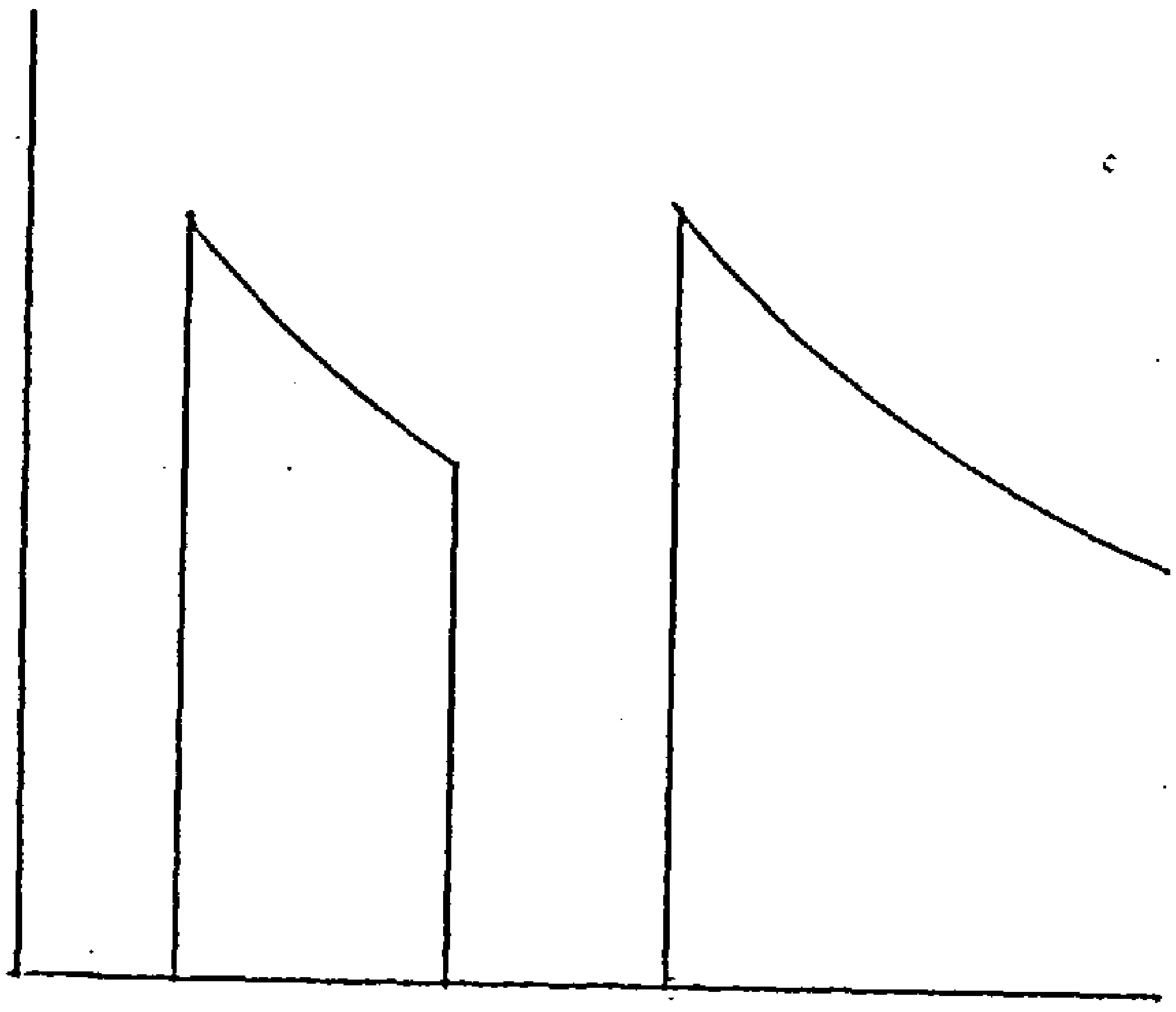


Fig. 1.4.4

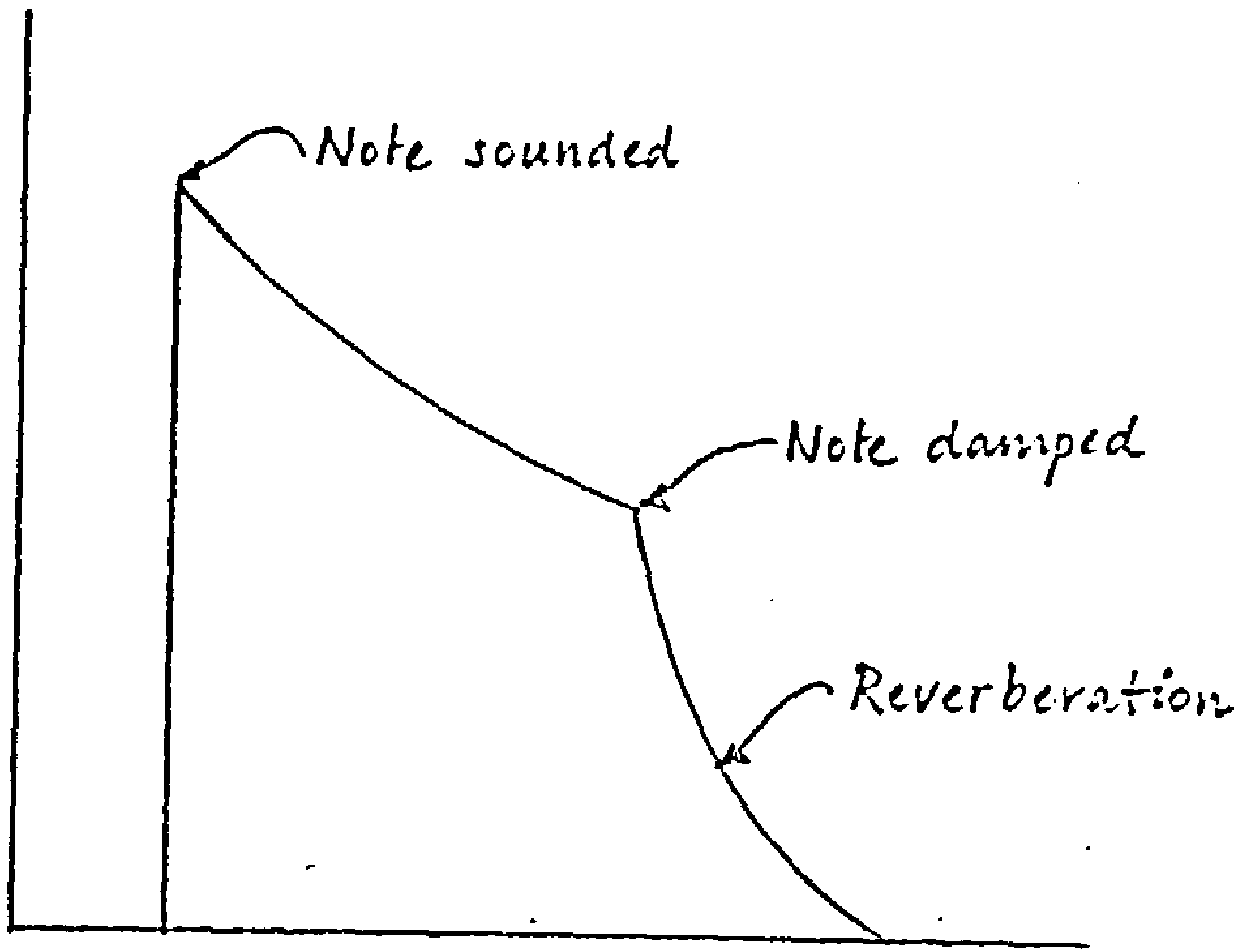


Fig. 1.4.5

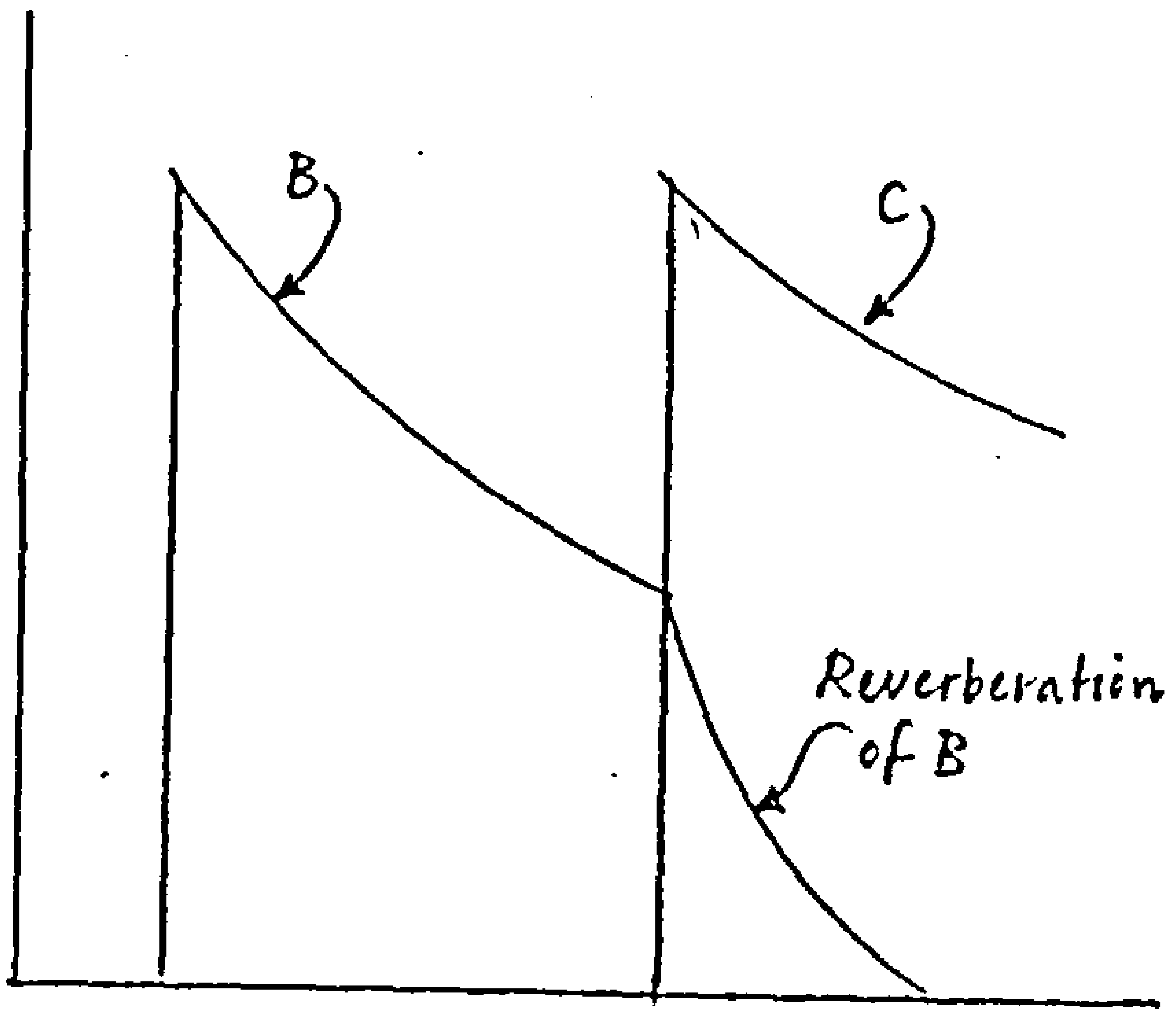


Fig. 1.4.6

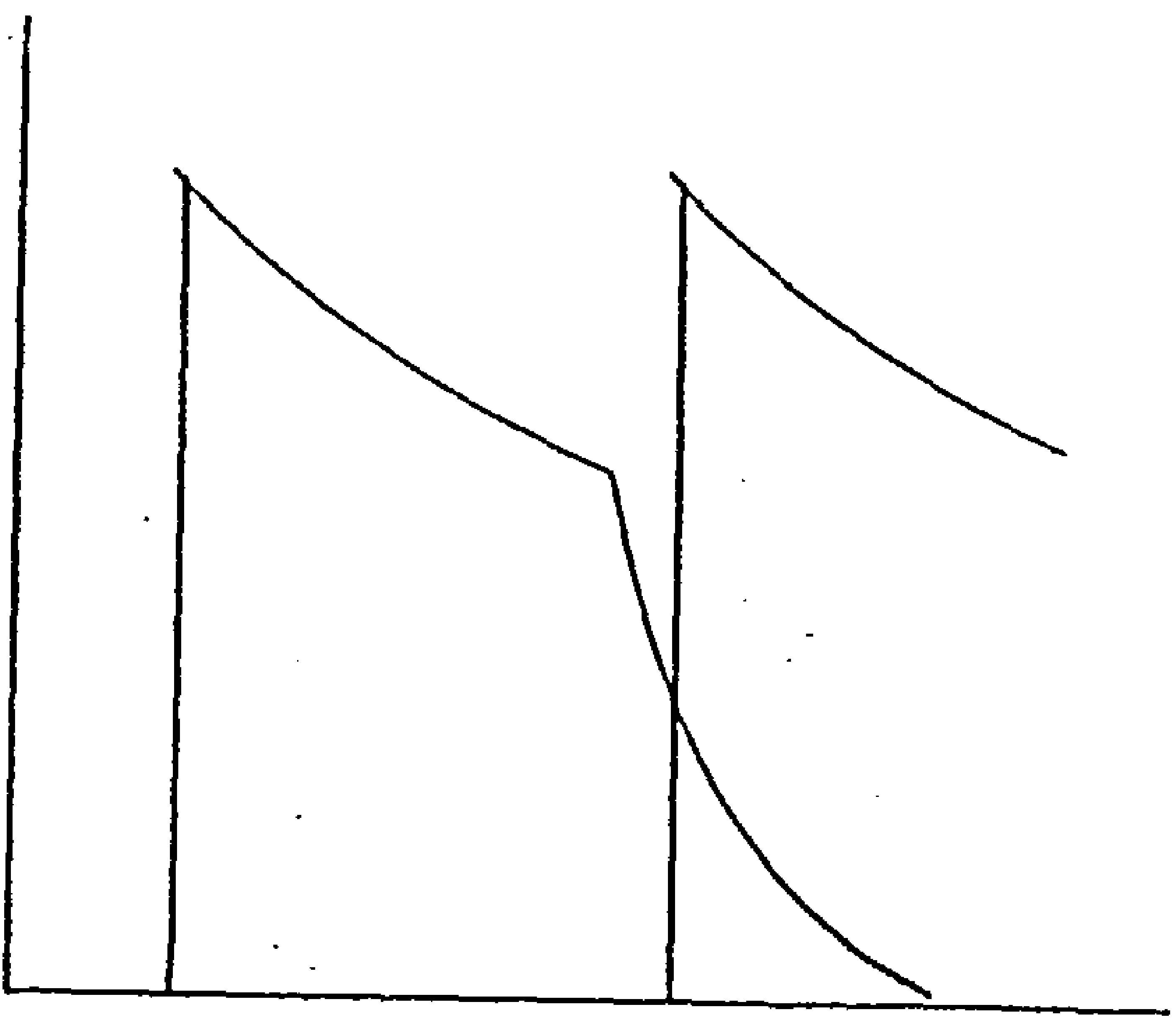


Fig. 1.4.7

forte proper, is intended to be played using the pedal as the rule, rather than the exception. The pedal of course causes the overlap of whole groups of notes. Even in eighteenth century music, it seems that quite a lot of overlapping was intended (Steglich, 1970).

Sometimes the composer intends two notes to be separated, that is, having a short silence between them (Fig.1.4.4). This is indicated by the term "staccato" (or by printing a dot over each note). The extent of the gap between the notes is not defined, so a sequence of notes to be played with a high gap / sounded note ratio is sometimes marked "staccatissimo". On the other side of legato, where notes are to be overlapped by using the fingers rather than by the pedal, the indication "legatissimo" is sometimes used. Thus there is a complete spectrum as follows:-

staccatissimo - staccato - non legato - legato - legatissimo

Of these five terms, only legato has a clearcut definition. Even then, there is some confusion in terminology. The point is that Fig.1.4.3 represents a piano in non-reverberating surroundings, for example out of doors. In this case damping takes place virtually instantaneously. However, the situation is very different indoors. A concert hall is usually designed to have a reverberation time of 1 to 1.5 sec. This means that there is still a considerable amount of sound "floating about" after the piano has stopped producing it. This is illustrated roughly in Fig.1.4.5, which assumes an exponential decay of the reverberations.

So now what do we mean by "legato"? If B and C are sounded with no break as before, but in reverberating surroundings, then the note C will overlap the reverberations of B (Fig.1.4.6). To many ears this may sound quite muddy in effect. Perhaps then we should define "legato" as a connection which involves a short gap to compensate for reverberations as in Fig.1.4.7.

To make matters more complicated, the rates of decay of both the sounded note and the reverberation depend on pitch, the higher notes decaying more rapidly. Thus, in order to get the same effect of smoothness at different parts of the keyboard, the degree of connection has to be compensated, with lower-pitched sequences of notes being more detached than higher-pitched ones.

It is well worth making a precise definition of "legato" as it has a great effect on methods of technique. Most authors (particularly Schultz) take the view that, if one key is raised at exactly the same instant that the next one is depressed, then everything will turn out satisfactorily. But if one is playing, for example, a Bach fugue by this method, then the top part will appear too thin and the bottom part will appear too thick. Really, this stems from a failure to distinguish between legato movements and legato sounds. In this thesis, "legato effect" will refer to sound, and "legato fingering" will refer to movements.

There is one further complication. The pedal mechanism can usually be manipulated to a state where it is neither fully damping, nor entirely free of the strings. In this condition, a note is imperfectly damped when it is released. Thus the reverberation time is effectively increased and joins can be made more legato. However there is a slight modification in tone due to a slight amount of sympathetic vibration in the other strings. As this technique is a question of aesthetics rather than anything else, it will not be pursued further in this thesis.

In the rest of this thesis, the fine-scale structure just discussed will be referred to as "connectivity".

1.5 MUSICAL STRUCTURE : GROUPS

A musical score is, at first sight, a jungle of musical symbols. In order to have a sound technical grasp of the music, it is necessary for the performer to analyse its structure. This involves breaking down the collection of symbols which comprise the score into small groups, each one of which can be recognised as a familiar structural subunit. This section of the thesis deals with the possible ways in which notes (as opposed to other musical symbols) can be arranged, and how these arrangements are classified conventionally. This enables the standard musical terminology for these groups to be introduced.

To begin with a simple concept: A collection of notes which are all played simultaneously is called a "chord".

Next, let us consider the class of groups which consist of single sequences, where a single sequence is a collection of notes which follow each other one at a time. There are eight major varieties of single sequences:-

1. Repeated notes. Example : CCCC...
2. Oscillation of consecutive notes (either a tone or a semitone apart). Example : CDCDCD... This is known musically as a "trill".
3. Oscillation of nonconsecutive notes. Example : CECECE... This is usually called a "tremolo".
4. Consecutive unidirectional sequence of notes. Example : CDEFGa'b'c'... This is an "ascending scale"; the reverse sequence would be a' descending scale".

5. Nonconsecutive unidirectional sequence of notes. Example : CEGc'e'g'... This is an "arpeggio". Arpeggios can be ascending or descending.
6. Varying selection of notes, closely packed. Example : CDBCAB...
7. Varying selection of notes, widely spaced. Example : CGCa'b'C...
8. Varying selection of notes, extremely widely spaced. Example : Cc'''. Such a pair is termed a "leap".

Now we can consider the class of groups which consist of double sequences - in this case the notes follow each other two at a time. This class is much bigger than the previous class, for not only do the eight previous patterns occur, but for each one of these patterns, the spacing between the members of each pair is a further variable. The term "a passage in thirds" refers to a double sequence in which this spacing is constant throughout, in this case a third. For example, the sequence : $\substack{\text{CDEF}\\ \text{ABCD}}$...(where superimposition implies simultaneity) is a special case of such a passage, namely a "scale in thirds". By convention, where piano playing is concerned, the nomenclature of double sequences is usually reserved for double sequences played by one hand only.

But enough of this; in the matter of grouping, one can rapidly become bogged down by terminology and definitions. Sufficient material has been presented here to serve the rest of this thesis.

1.6 MUSICAL STRUCTURE : A PRACTICAL ASSESSMENT

It is necessary for the originator of any technical method, or for the aspiring pianist, to have a basic set of problems on which to focus his attention. Many writers have a very unbalanced view of piano playing theory; indeed, the reader sometimes gets the impression that the amount of discussion on a topic is inversely proportional to its complexity. There follows now a list of groups which, it is felt, form a fairly well-proportioned set of technical problems. The numbers in the list refer to those of the eight types of group described in the last section.

Single sequences : 1,2,4,5,6,7,8

Double sequences :-

- (a) A third apart : 2,3,4
- (b) A sixth apart : 2,4,5
- (c) An octave apart : 1,6,7

Because the keyboard is made up of two different types of key, the technical problem involved in playing a group depends very much on the order in which black and white keys occur; therefore, each group just listed should be studied through several configurations i.e. several different selections of black and white keys.

Other factors which affect technical problems are dynamics and the relative strengths of the fingers; these points will be discussed later.

Of course, there are always some problems which occur which will not fit into any category, and for these, ad hoc solutions must be found. A list of prize examples is given in Sec.1.9.

1.7 MUSICAL STRUCTURE : DYNAMICS

The last two sections have looked at the structure of notes. However, notes are not the only symbols which appear on the score. There are further indications as to the manner in which the notes should be played; the variables involved are usually termed "dynamics". These dynamics are now categorised :-

1. Speed. The general rate of occurrence of the notes, termed "tempo", varies greatly. Almost invariably the technical difficulty involved in playing a group increases as the tempo increases.

2. Amplitude Level. For the piano, and indeed for most instruments, it is possible to vary the amplitude, i.e. loudness, of any note. Thus the amplitude level of a group of notes constitutes a dynamic variable. A very low amplitude level is termed"pianissimo" and a very high level is termed "fortissimo". A piano is capable of producing a continuous spectrum of amplitude levels between these extremes - a pianist should be similarly capable.

3. Amplitude Fluctuation. There is no reason why all the notes in a group should be played at the same level of amplitude, and so we must consider the degree of change of amplitude level to be a separate dynamic variable. There are two ways in which this change can occur. Firstly, there may be a continuous change in amplitude throughout the group (termed "crescendo" when increasing and "diminuendo" when decreasing). Secondly, there may be a discontinuous change where one or more notes are on a distinctly different level from the surrounding notes (termed "sforzando" for a sudden increase and "subito piano" for a sudden decrease). The problem of controlling amplitude fluctuation is one of ensuring that there are no unwanted bumps. therefore the problem is often called that of "evenness". A discontinuous change will be called here "accentuation".

4. Connectivity. This has already been discussed in Sec.1.4, where it applies to two notes. Clearly the idea of connectivity can be extended so that it applies to a whole group.

The above four dynamic conditions are not mutually exclusive, but simultaneous. For instance, a piece to be played rapidly, very quietly, evenly, and staccato with large amounts of accentuation is quite common.

1.8 MUSICAL STRUCTURE : A BRIEF HISTORY

Looking at the whole of the literature of piano music in retrospect, it becomes quite clear that there are four distinct eras. The first of these (pre - c1700) saw music established as an art form; few keyboard compositions worthy of note were composed during this time. In the second era (c1700 - c1800), which is sometimes known as the "Classical" period, the two major social forces were the Church and the aristocracy, and composers were almost invariably employed in these circles; hence their music is, by and large, conservative and self-confident. The third era (c1800 - c1900) is usually called the "Romantic" period. During this time, the bourgeoisie came to power, composers became freelance and music was written for the masses. As a result, an element of showmanship entered into solo music, and for this reason most of the worst technical problems encountered in piano playing belong to the nineteenth century. The fourth era (c1900 onwards), referred to as "Modern" or "Contemporary", has produced a wide variety of music, much of it experimental and much of it written in a disillusioned frame of mind.

The transitions from the second to the third era and from the third to the fourth era both occurred with remarkable speed. It is interesting to speculate to what extent the first of these changes was caused by current social upheavals (the French Revolution, the Industrial Revolution, etc.), and how much the second change was affected by contemporary scientific iconoclasm (the discoveries of Darwin, Freud, Curie, Rutherford, Einstein, etc.) together with the first world war. It is significant that other art forms such as painting and literature underwent similar changes.

The main composers of keyboard music in the Classical period were J.S. Bach, D. Scarlatti, Haydn and Mozart. Bach wrote in the "Baroque" style which uses very rich textures composed of sequences which are in a constant state of interweaving. Haydn and Mozart wrote in the later "Rococo" style which uses very light textures, often little more than a single sequence of notes. Scarlatti had a personal style and was the first great keyboard composer to exploit technical difficulty for its own sake.

The Classical and Romantic periods were bridged by Beethoven and Schubert. Beethoven was responsible for a rapid development of pianoforte style and manufacturers were forced to produce bigger and stronger pianofortes in order to accommodate his music; for the first time, strength and stamina became important factors in piano playing.

The Romantic period produced many great composers of piano music: Chopin, Liszt, Schumann, Mendelssohn, Brahms, Tschaikowsky and others. Liszt was the prime example of a pianistic wonder and wrote music which would best display his dazzling technique. Chopin mixed virtuosity with real artistry and showed great resource in exploring new musical structures.

In the present century piano composition has gone into decline although Prokofiev, Bartok, Stravinsky and Messiaen have written in the modern idiom. As many composers of this age believe that the piano is an instrument to be thumped, a new crop of technical problems has arisen.

1.9 MUSICAL STRUCTURE : EXTREME EXAMPLES

Piano playing is not the gentle, relaxed activity it may appear to be to the uninformed listener. Some of the technical difficulties encountered in playing the works of the great composers are positively fearsome. This section contains a selection of the very worst problems which occur; all these examples are highly notorious, and even the greatest pianists find them almost impossible to play.

But first, a few introductory remarks. For any difficult passage, a system of "fingering" must be worked out, which means that it must be carefully decided which fingers are to play which notes. The fingers are labelled : "1" for the thumb to "5" for the little finger (usually referred to in this thesis as "digit 1" to "digit 5"); these numbers are often written in the score, just above or below the notes. In some of the examples given here, fingering is indicated; this implies that the fingering given is the only practicable one, all others being out of the question. Where no fingering is given, there is more leeway. (It should be remembered that each example is, in the original, surrounded by further groups of notes which may themselves influence the fingering of the example). Digits 4 and 5 are endowed with considerably less strength than the other three digits, and they are usually known as "the weak fingers". Very often a severe technical problem arises because these fingers are the only ones which are left to play a particular note or notes, and the dynamics may be such (i.e. fast and loud) as to cause almost impossible loading. In any form of sport, fatigue is a great problem, and such is the case with piano playing. Many groups of notes in the literature are especially difficult to play simply because by the time they arise, the pianist has reached a state of muscular exhaustion.

Each example, other than the first, is illustrated in musical notation in Fig.1.9.1. A brief note is given as to the nature of each technical problem; some of the reasons given may not become entirely clear until the whole thesis has been read. The tempo is indicated in each example: " = " indicates the composer's marking, " ≈ " indicates that the composer has not given a marking and that I have estimated the speed intended. The term "etc." indicates that the basic pattern shown continues for some time; very often this creates a stamina problem. All examples are for the right hand unless otherwise stated.

1.9.1 List of Extreme Examples

Ex.1. Bach. Almost any fugue (not illustrated here)

The general difficulty is that one hand is expected to play in two or even three dynamically different ways. e.g. digits 3,4 and 5 may be playing staccato and pianissimo whilst digits 1 and 2 are playing legato and mezzo-forte.

Ex.2. Bach. Prelude Dmaj. Well-tempered Clavier I. ♩ ≈ 120.

Needs great control over evenness. Great length of passage creates nervous/mental fatigue.

Ex.3. Scarlatti. Sonata L.415,Kk.119. ♩. ≈ 80.

Speed, lateral accuracy.

Ex.4. Beethoven. Sonata Cmin.Op.111. ♪. ≈ 48.

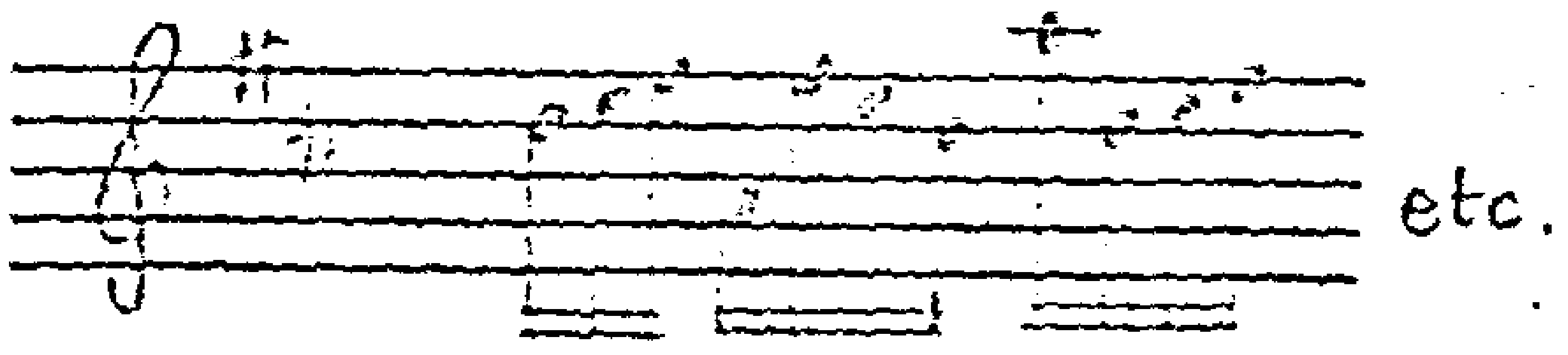
Speed and stamina from weak fingers, synchronisation.

Ex.5. Beethoven. Sonata Cmin. Op.111. ♪. ≈ 48.

Speed and strength from weak fingers, synchronisation.

Ex.6. Beethoven. Sonata Bflat Op.106. 𝅗𝅥 ≈ 90 (?)

Speed, general overloading of weak fingers,synchronisation.



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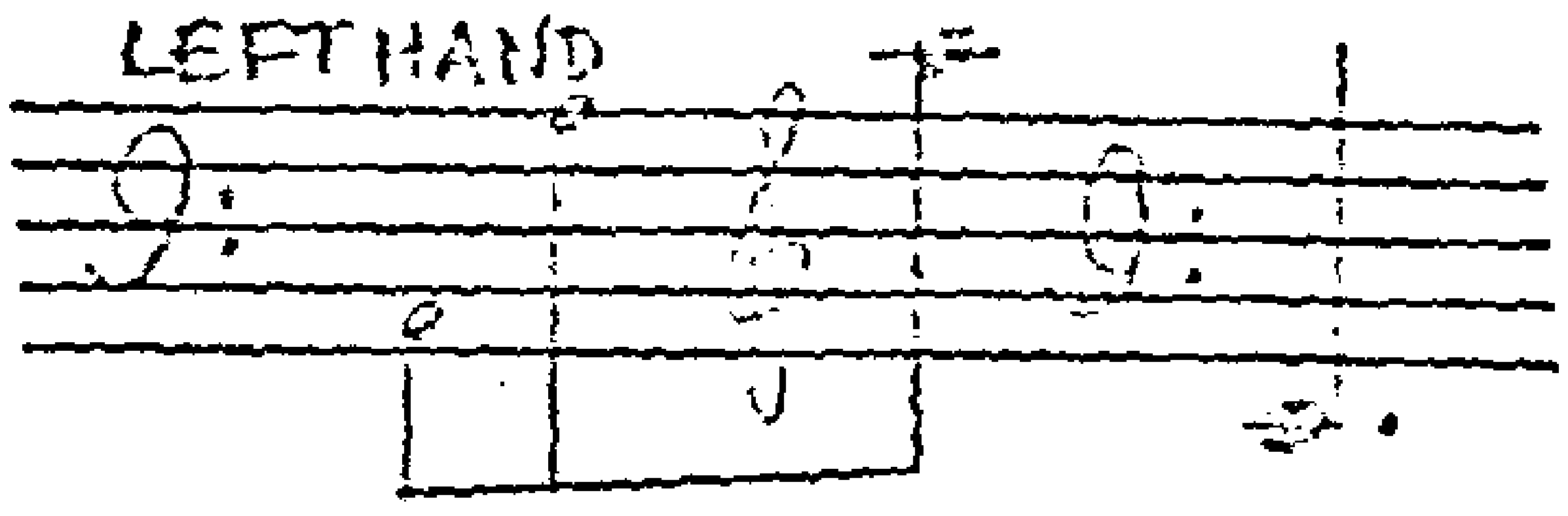

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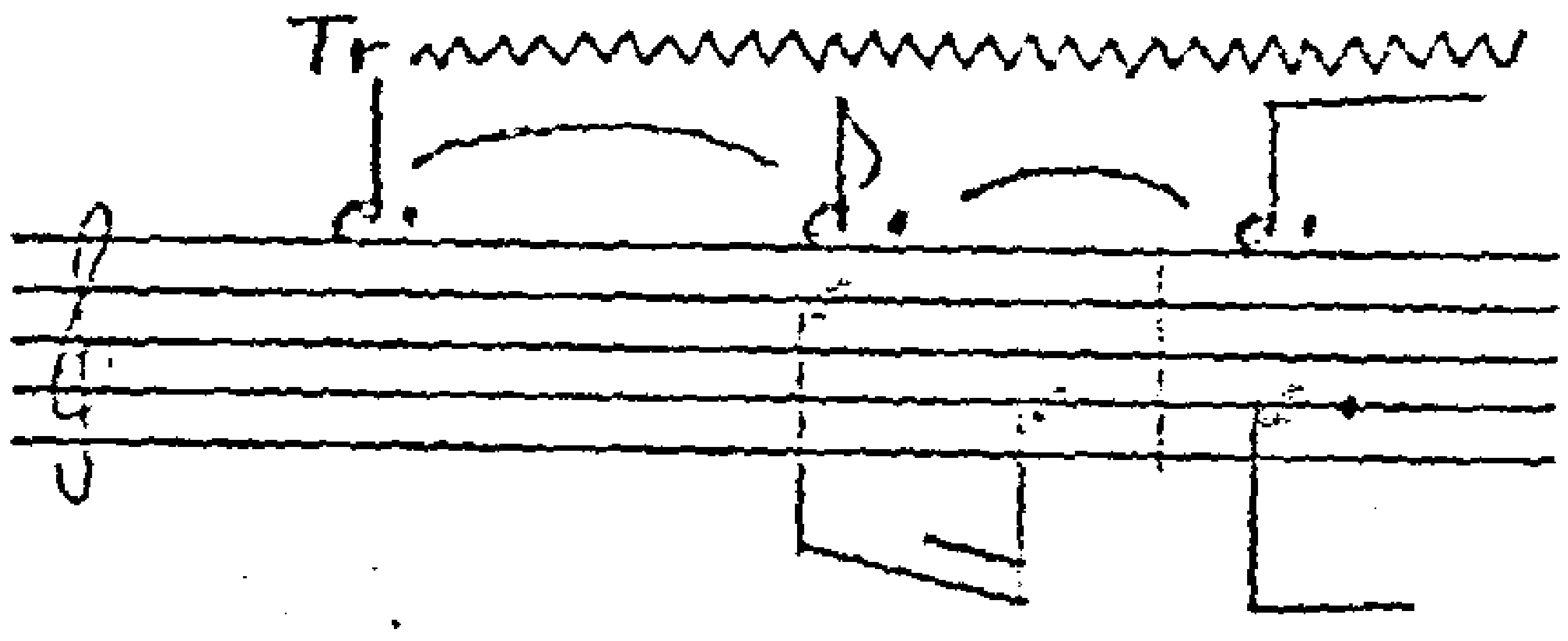

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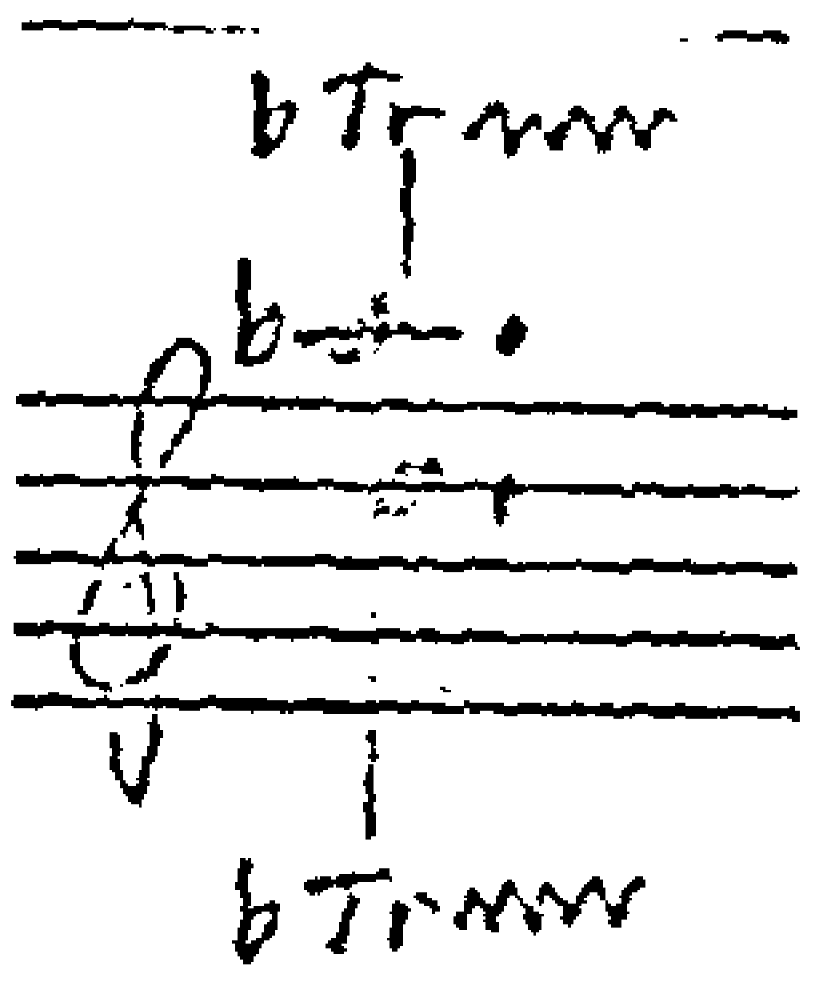

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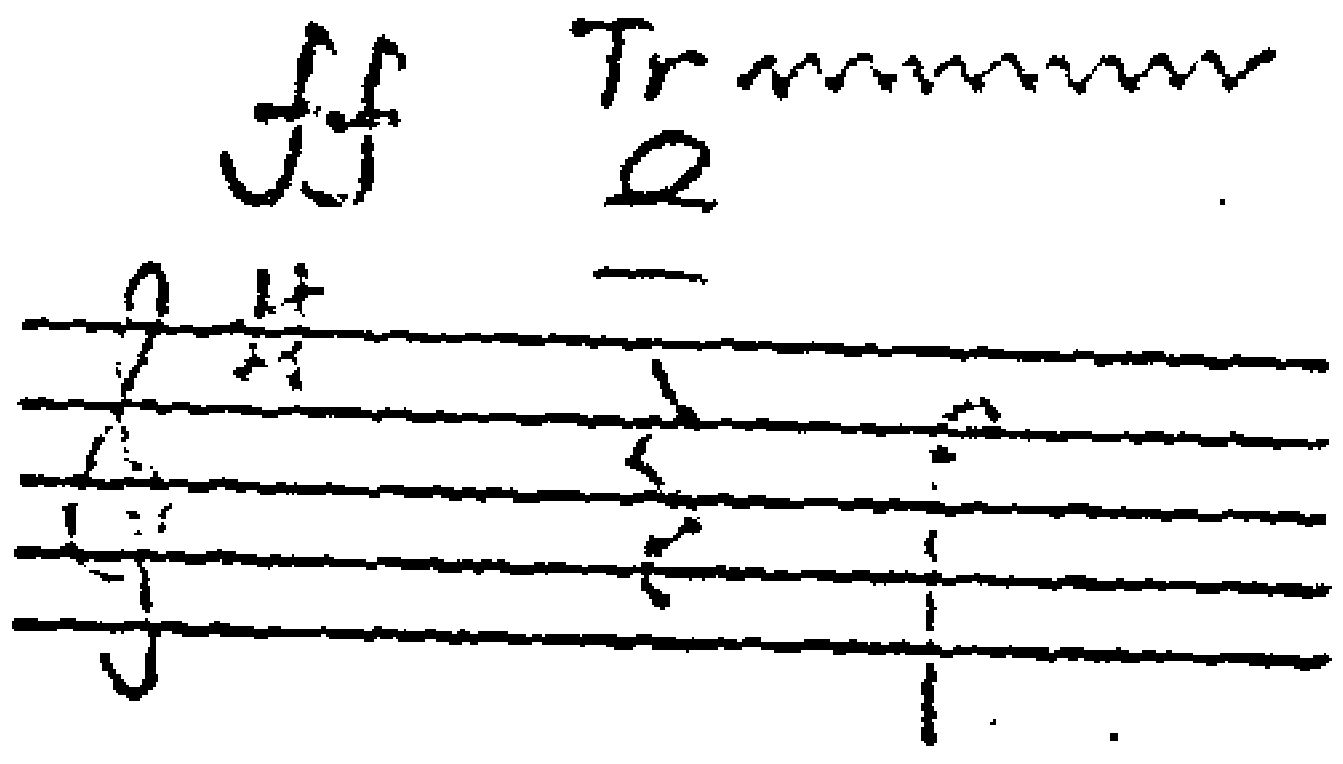

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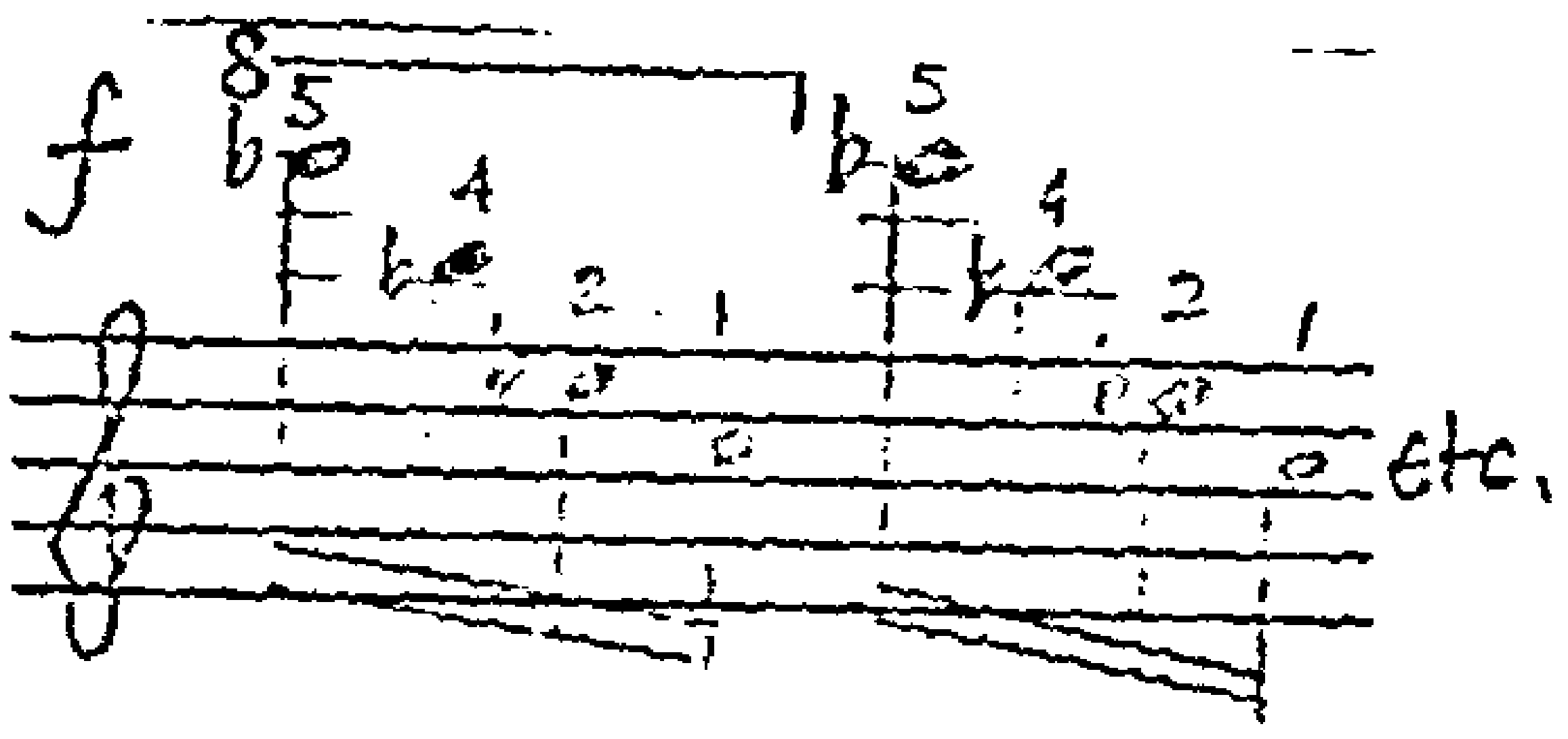

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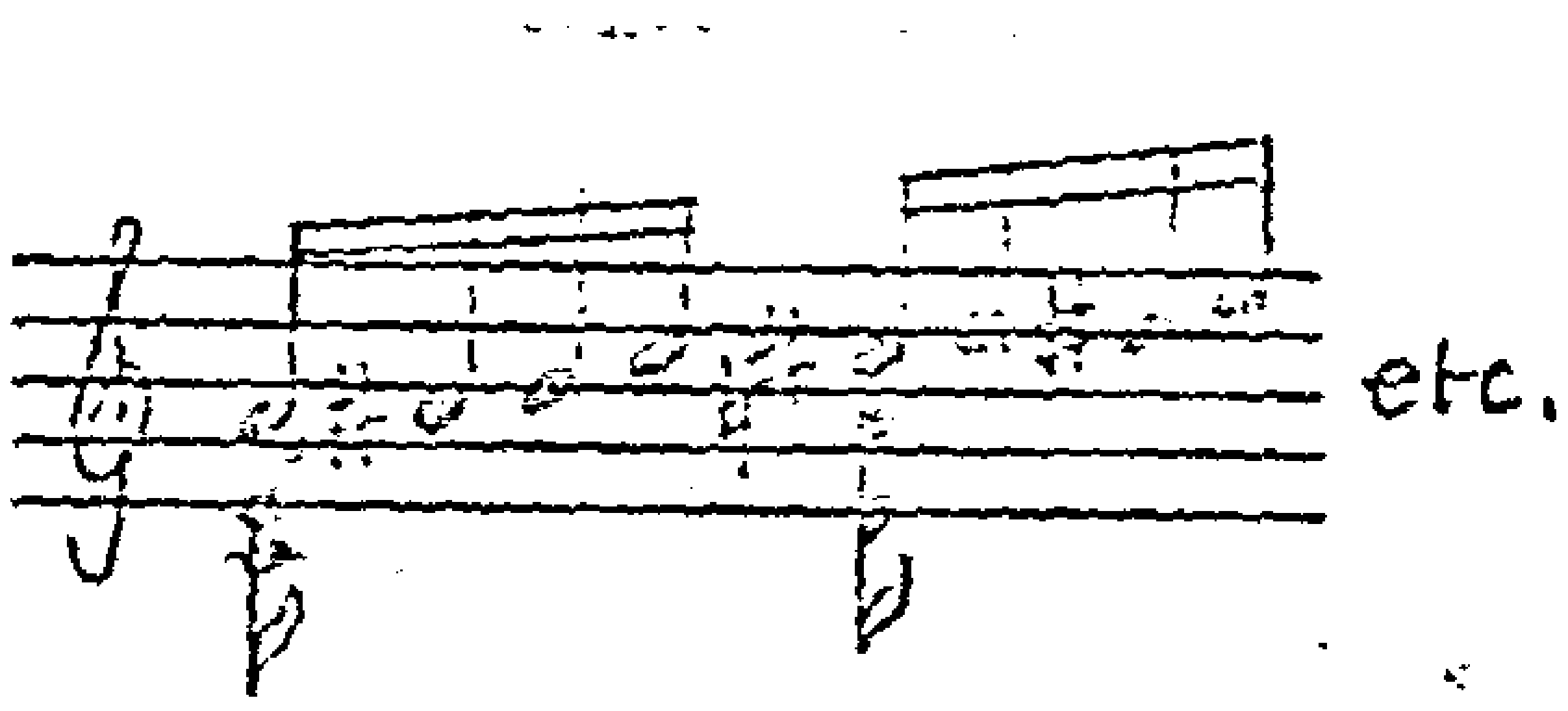

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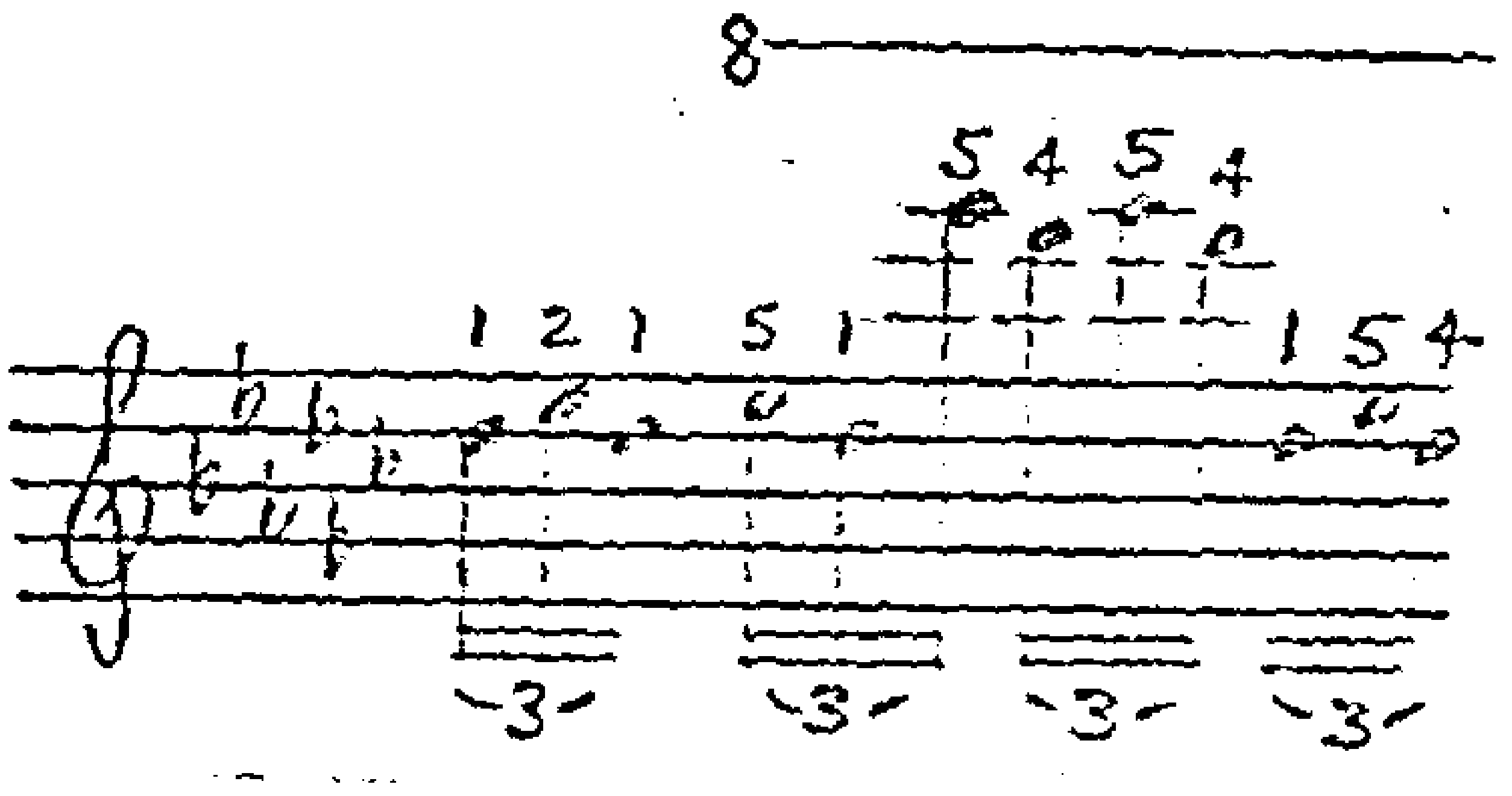

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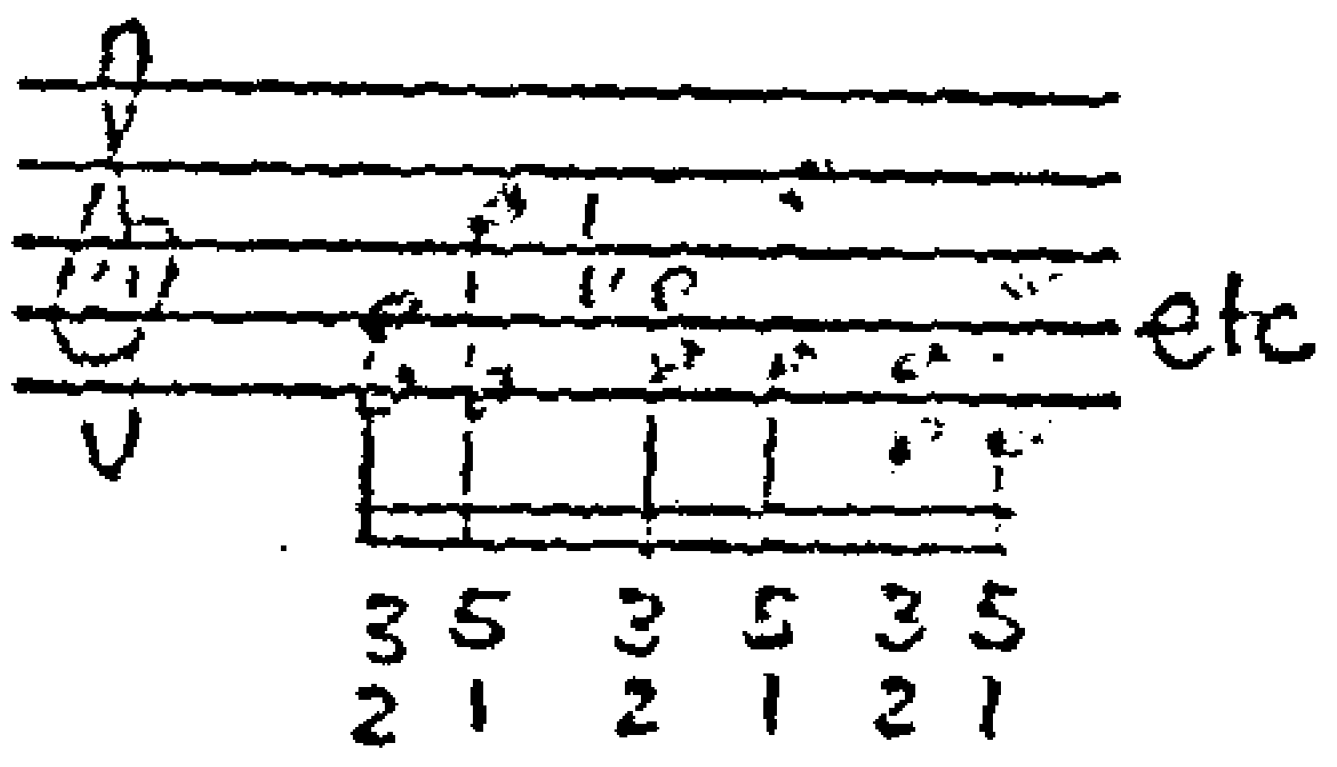

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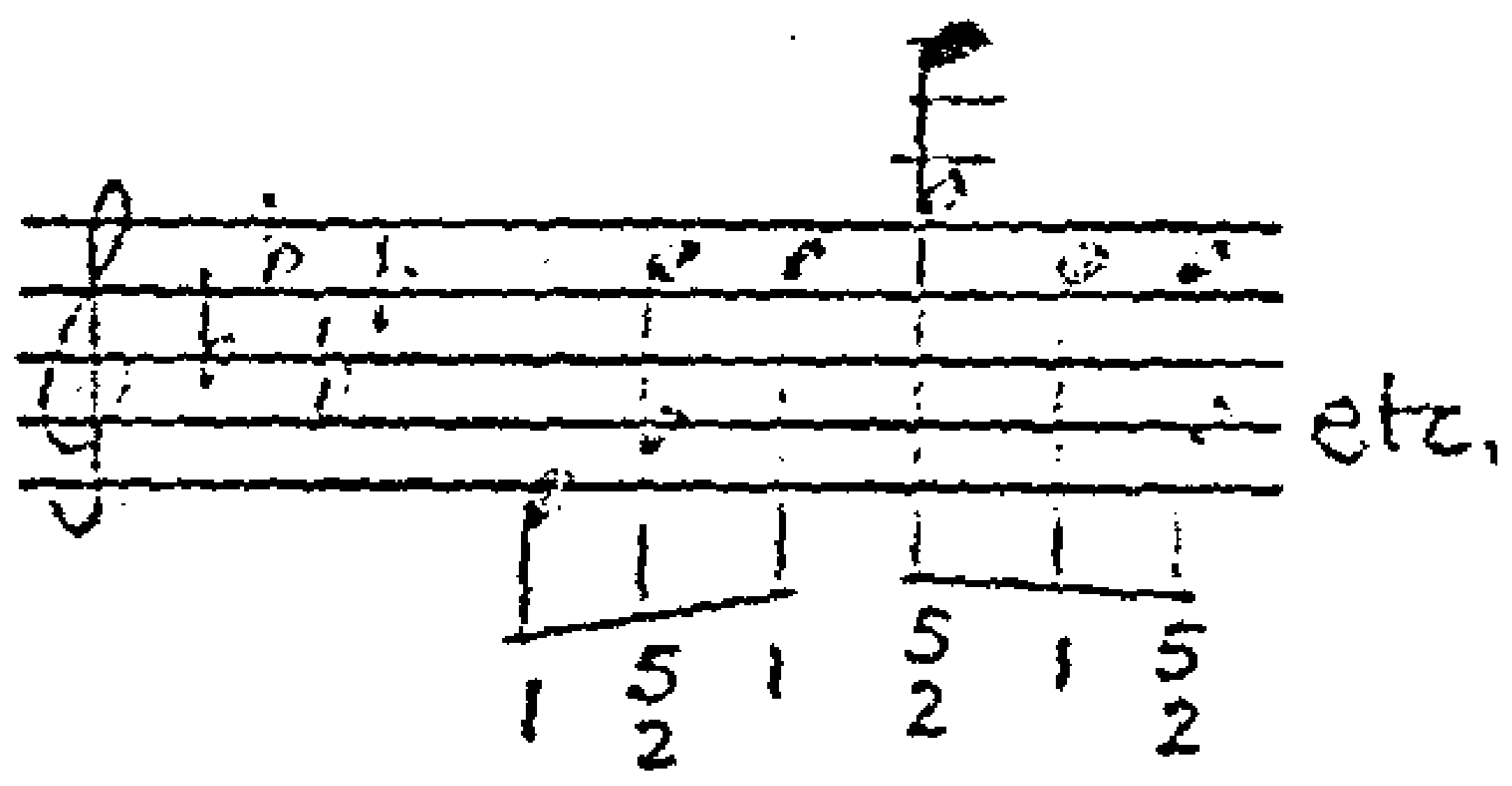

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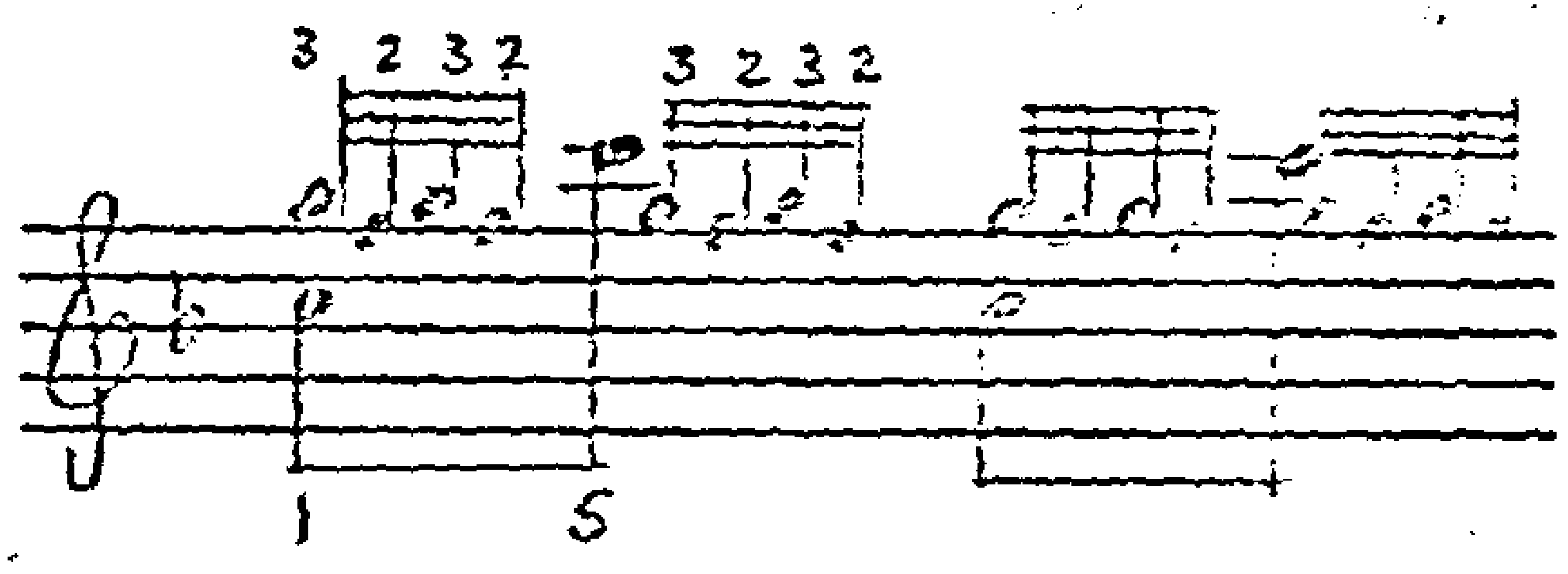

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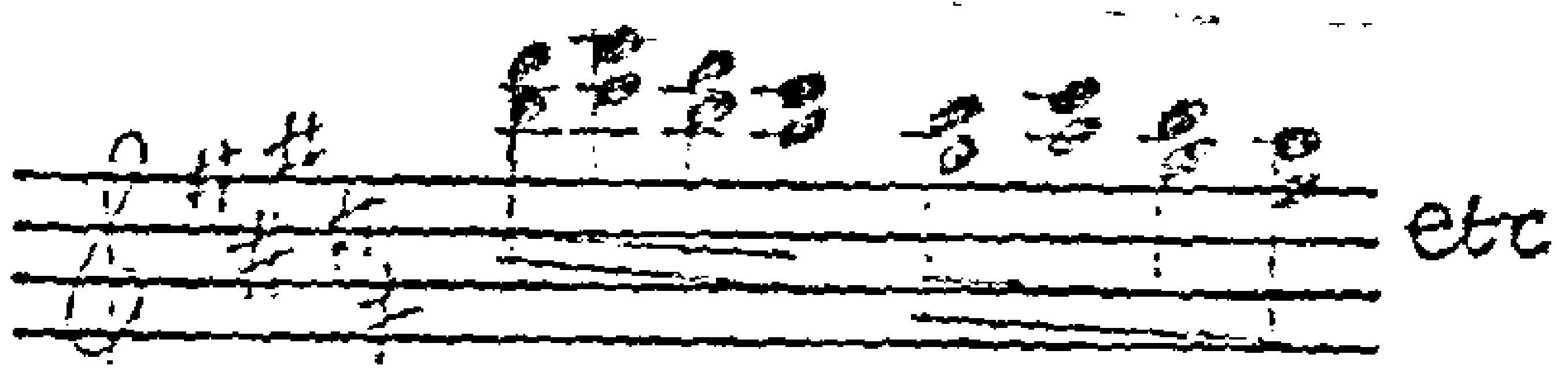

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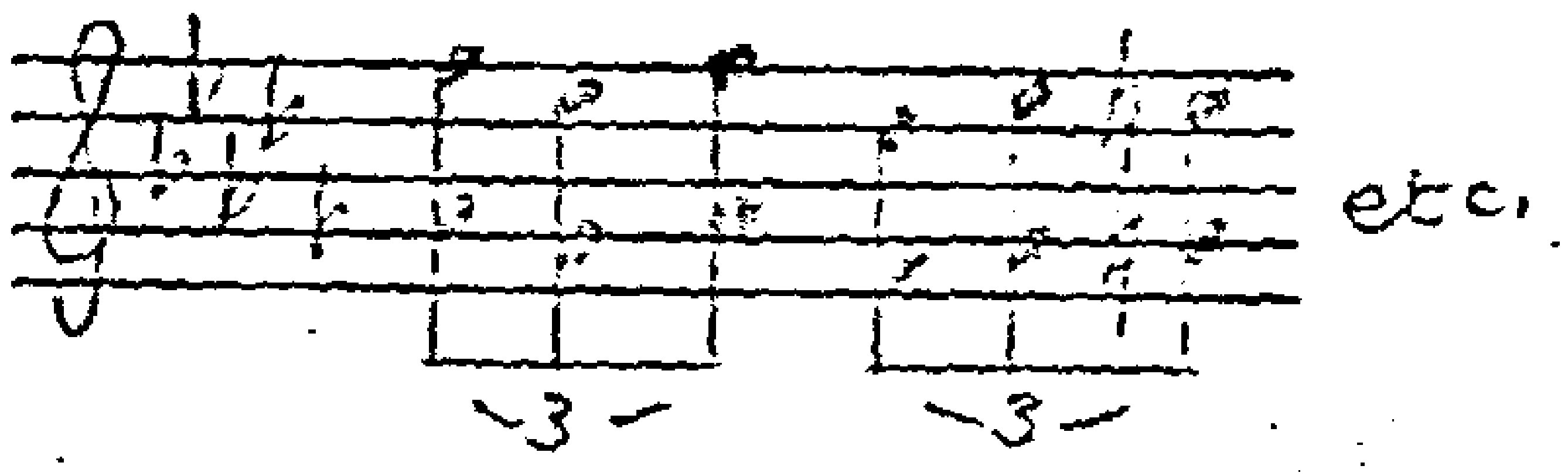

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Ex.7. Chopin. Etude Op.10, no.1. ♩ = 176.

Speed, stamina, weak fingers need strength, very awkward stretches, lateral stability.

Ex.8. Chopin. Etude Op.10, no.2. ♩ = 144.

Speed, stamina, weak fingers need great agility, sudden snatches with remaining fingers.

Ex.9. Chopin. Etude Op.10, no.5. ♩ = 116.

Speed, power needed from weak finger, lateral stability.

Ex.10. Chopin. Etude Op.10, no.7. ♩. = 84.

Speed, stamina, very difficult to catch repeated note.

Ex.11. Chopin. Etude Op.10, no.10. 𝅗𝅥. = 80.

Speed, stamina, lateral accuracy, repeated note.

Ex.12. Chopin. Etude Op.10, no.11. ♩ = 76.

Great lateral accuracy needed from all ten digits.

Ex.13. Chopin. Etude Op.25, no.3. ♩ = 120.

Speed, evenness in face of inherent imbalance due to either side action.

Ex.14. Chopin. Etude Op.25, no.6. 𝅗𝅥 = 69

Speed, stamina, configurations of notes greatly impede progression of fingers, virtual repeated note.

Ex.15. Chopin. Etude Op.25, no.8. 𝅗𝅥 = 69

Speed, great lightness needed although fingers have continual awkward stretches.

Ex.16. Liszt. Etude "Feux Follets". ♩ ≈ 70.

Speed, delicacy, awkward stretches, repeated note, configurations of notes unhelpful.

Ex.17. Liszt. Etude "La Campanella", ♩. ≈ 72

Speed, lateral accuracy.

Ex.18. Liszt. "Mephisto Waltz". ♩ ≈ 110?

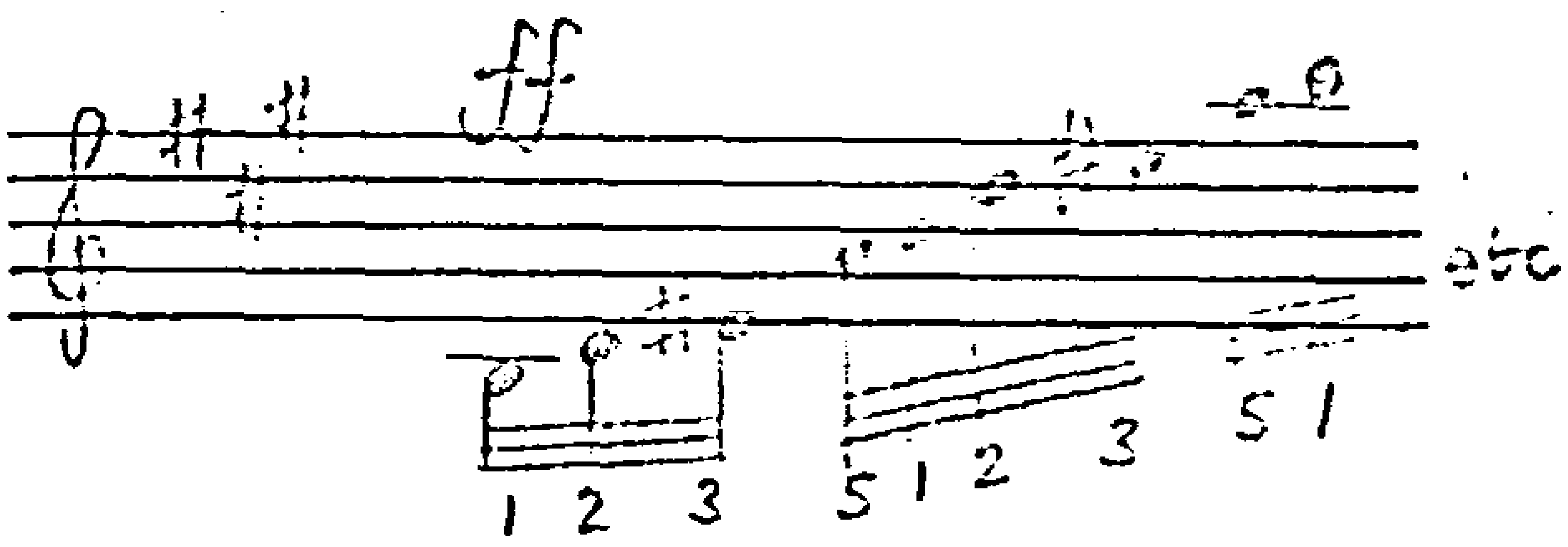
Speed, strength, awkwardly spaced arpeggio.

Ex.19 Schumann. Toccata. ♩ ≈ 126.

Speed, stamina, weak fingers need strength, wide stretches cause fatigue.

Ex.20. Tausig. Arrangement of Schubert's "Marche Militaire" ♩ ≈ 112.

Total overloading of weak fingers, due to very large stretch.



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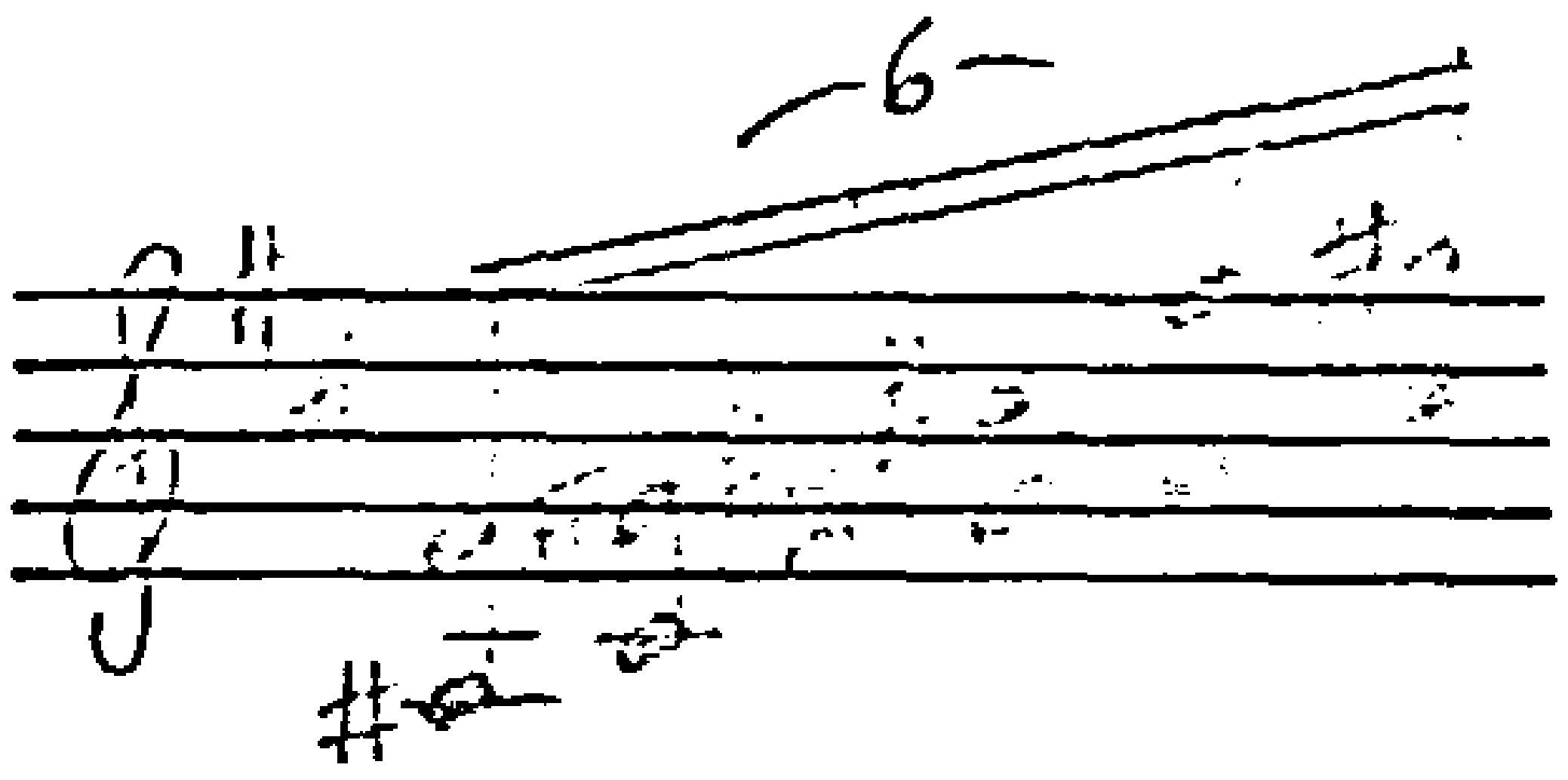

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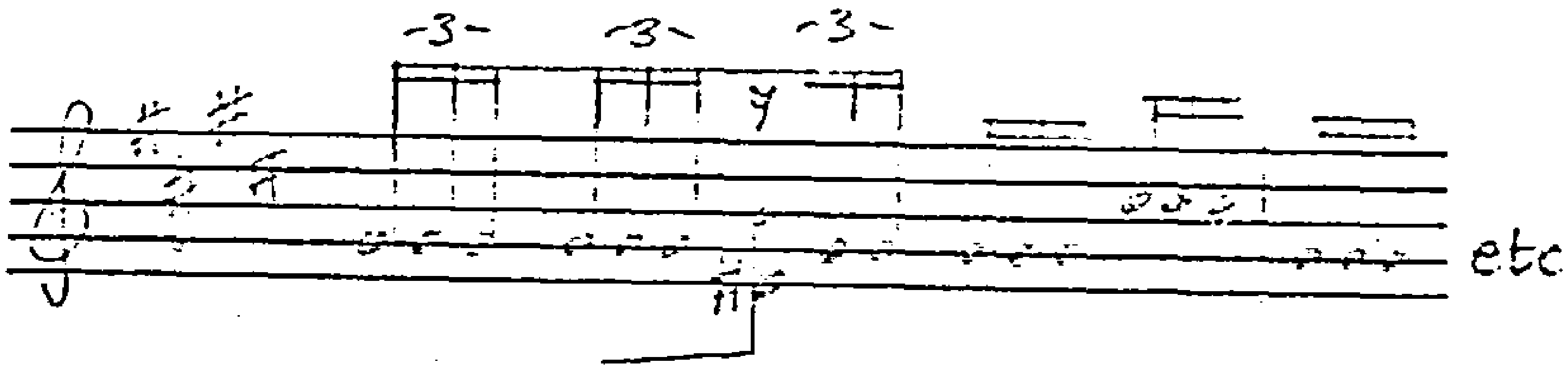

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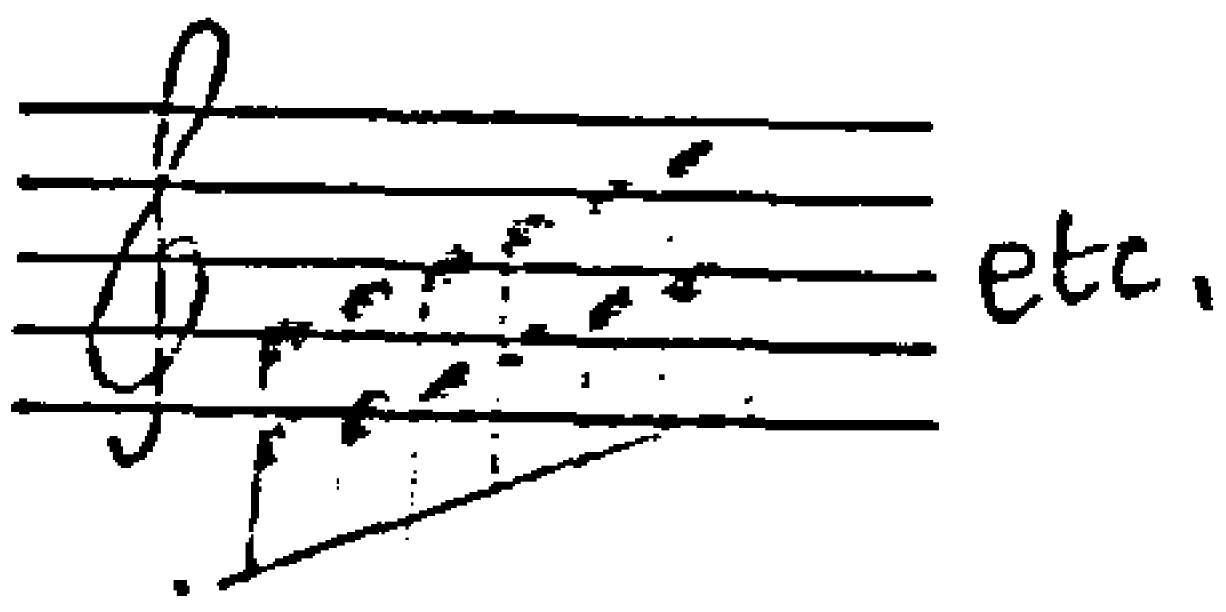

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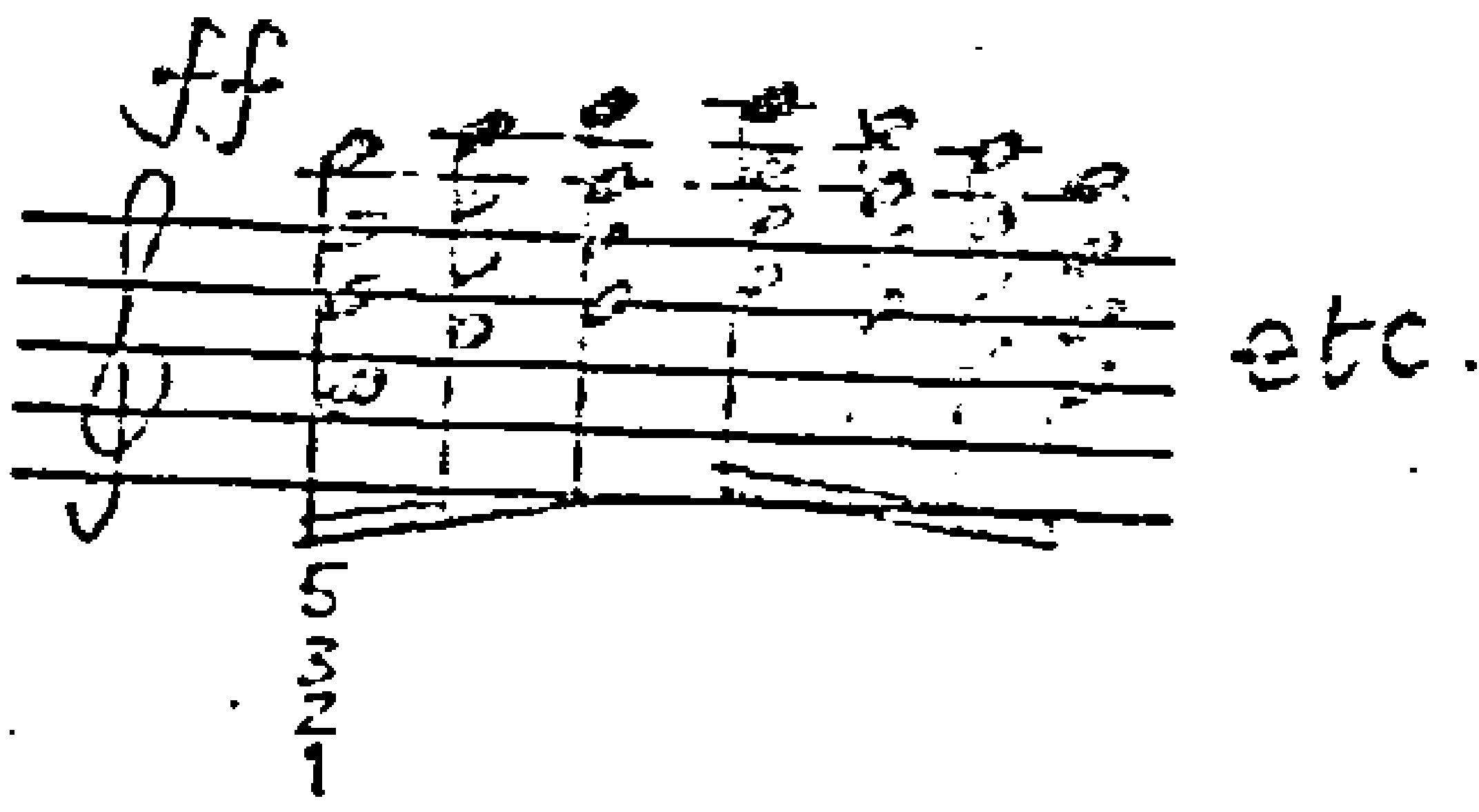

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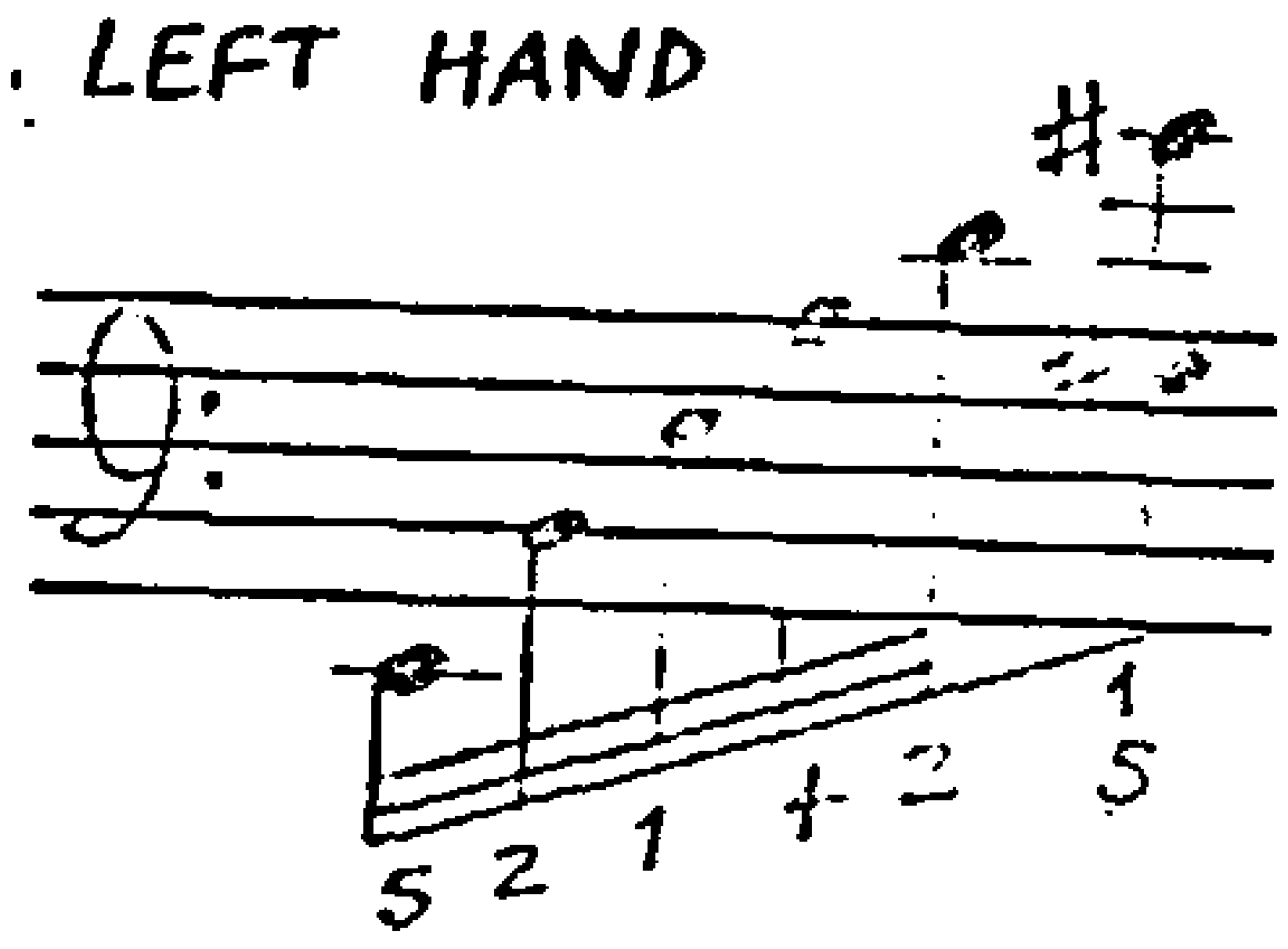

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Fig. 1.9.1

This list does not cover more than a tiny fraction of the problems in the musical literature, and it is of course a personal selection. It should be regarded as representative rather than comprehensive.

Ex.21. Brahms. Concerto no.2. ♩. = 92.

Speed, strength and stamina needed from weak fingers.

Ex.22. Brahms. Concerto no.2. ♩. = 92.

Speed, lateral stability, configuration of notes upsets progress of fingers.

Ex.23. Ravel. "Alborada del Gracioso". ♩. ≈ 76.

Acutely fast repeated notes, lateral stability, general contortion.

Ex.24. Ravel. "Alborada del Gracioso". ♩. ≈ 76.

Double glissando. The hand must be dragged across the keys catching two notes at a time.

Ex.25. Rachmaninoff. Etude-Tableau. 𝅗𝅥 ≈ 72.

Repeated note in awkward position causing lateral instability.

Ex.26. Stravinsky. "Russian Dance" from "Petrushka". ♩ = 116.

Explosive power needed from arm.

Ex.27. Stravinsky. "Russian Dance" from "Petrushka". ♩ = 116.

Impossible.

Ex.28. Bartok. Sonata. ♩ = 120.

Great strength needed, but the arm is prevented from producing a proper action by the held note.

1.10 SOME PROPERTIES OF HEARING

The ultimate criterion of all piano playing is of course that it should be well received by the audience; in other words, that the aural sensation of the listener is agreeable. It is relevant therefore to consider here some of the basic mechanisms of hearing - this subject has been neglected far too much in the musical literature, as will become apparent later. In making such a study, it is vitally important to distinguish between the ear and the brain. The ear is a transducing device which converts vibrations in the air into nervous stimuli. The brain is an exceedingly complex creation about which little is known; it is the brain which assesses the nervous stimuli produced by the ear.

The ear is capable of detecting sounds which vary over a considerable range of frequency (approximately from 50 to 20000 Hz), although its response is not constant over this range (the ear is most sensitive in the region of 1000 Hz.). The frequency (or "pitch") of the vibrations is converted to nervous stimuli in a logarithmic fashion, so that any pair of notes whose frequencies are related by a constant factor are always gauged by the ear to be a constant distance apart. Many of the sensing devices of the body have logarithmic input-output characteristics and in consequence are said to follow the Weber-Fechner Law.

The brain itself uses the ear as a tool of detection. Although the brain may be well aware of minute changes in pitch (as for example in listening to a badly-played violin), it prefers to think in terms of discrete changes of pitch, each quantum (a"semi-tone") being a change in frequency by a factor of $2^{1/12}$. (This statement is true for the system of "equal temperament" used on the pianoforte. For instruments of variable pitch, e.g. the violin, a far more esoteric system is used, which involves very slight departures from these intervals (Taylor, 1965)).

It is as if the brain organises a matrix for itself and discriminates the incoming stimuli, recognising the stimuli as belonging to either one domain of the matrix or another. Under this hypothesis, those people with "perfect pitch" have a fixed matrix, and those with "relative pitch" have a sliding matrix which orientates itself happily to whatever system of pitches is used by the performer. (For a pianist, one could well argue that perfect pitch, usually considered a wonderful gift, is very much a mixed blessing).

These properties of frequency assessment are well known, but what about the assessment of amplitude? The ear reacts to amplitude in the same way as frequency i.e. logarithmically, but this leaves us with the question of what the brain does with the information.

There is an apparently little-known article by Whipple (1928) who discusses, qualitatively, the discrimination of amplitude levels. His inquiry stems from a study of the once-fashionable "Duo-Art" reproducing piano. This instrument is basically a grand piano, but it is played, not by human agency, but by a marvellous mechanical system. Each hammer can be propelled by a jet of compressed air, under the control of a punched paper tape device. So fine is the degree of control that each note can be given no less than 16 different amplitude levels. Now Whipple, as a result of his experiments with musically-skilled listeners, reaches the conclusion that some of these amplitude levels are superfluous, and that a set of seven amplitude levels would be sufficient from a subjective point of view. In other words, he reckons that the brain is capable of distinguishing only about seven different levels within the range of amplitude which can be achieved on the piano. This seems very plausible, especially when one considers that the composers of piano music, when indicating amplitude levels, generally work with between five and ten levels.

1.11 PERFORMANCE SPECIFICATIONS

A pianist has many variables to work with and he must be highly aware of their relative importance. This section gives a brief indication of the sort of decisions which a pianist faces.

Firstly, to what extent should a score be obeyed? There is always room in a composition for personal expression; indeed, if there were not, most of the musical content would vanish. An individual interpretation is the result of manipulating, amongst others, the following variables: note selection, level of amplitude, degree of amplitude fluctuation, tempo, connectivity and pedalling. The amount of adjustment of these variables which an audience will accept without considering the pianist to be taking undue liberty is something which is in a constant state of flux; in fact, the word "fashion" is not inappropriate. Nowadays, a pianist is expected to select notes with scrupulous regard to the composer's intentions. However, in choosing amplitude levels and amplitude fluctuation he is allowed considerable licence; and as for pedalling, this is something that is rarely indicated precisely by the composer, and the pianist is given a free hand (or, rather, foot). Both tempo and connectivity may be adjusted slightly, but in recent years, the public has grown less tolerant to their alteration. (An exception to this is in the music of J.S. Bach, who is still interpreted with remarkably widely differing degrees of connectivity).

Secondly, what values should these variables have if a pianist wants to consider himself a first-rate pianist? Obviously perfection is impossible, but one can lay down a few rather loose yardsticks as to what he is expected to achieve - performance specifications, one might say. Amplitude level is an easy thing to assess - at least, if one accepts Whipple's theories; simply, a pianist should be able to pass through all seven domains of amplitude. Again, it is tempting to be rather glib and say that evenness is just a question of keeping within one amplitude domain. Of all the variables, accuracy of note selection, or its lack, is the most obtrusive; most present-day pianists have a positive dread of playing a wrong note. But play wrong notes they invariably do - the degree of accuracy achieved is almost always ninety-something per cent, that is, for a good pianist; more of this in Chap.8. It is possible to give figures for tempo, but they depend very much on the type of passage played. A passage played by arm actions (defined in Sec.7.0) can be taken at speeds up to about 8 notes per sec. by a first class pianist, provided that the notes are close together, or perhaps even at nine notes/sec. if the notes are repeated. It must be made clear that in the matter of rapid arm actions, piano playing is very similar to athletics. In athletics, top competitors all perform around the same ceiling; there is only a small difference, numerically, in the performances they achieve. For a high-ranking pianist, a closely packed arm passage at 7 notes/sec. is something to scoff at; 10 notes/sec. is an impossible dream. It must be said further that those figures refer to very short bursts of action - the equivalent of a flat-out sprint for a runner. Stamina is another hallmark of the virtuoso; a first-rate pianist might be expected to keep up this sort of arm action for as much as five seconds at a time.

These are not the only technical requirements of a good pianist; for example, he must have excellent control over the occurrence of notes in time, that is, he must show little temporal inaccuracy when producing a rhythmically constant sequence of notes (or: he must reduce the amount of frequency modulation to an acceptable level).

1.12 SUMMARY

This chapter contains several statements which are more illustrative than accurate and many definitions which are by no means precise. However, it is hoped that any pure scientist reading it has been given at least an inkling of the sort of technical problems which are encountered in playing the piano.

2

A PREVIEW OF THE LITERATURE OF PIANO PLAYING

The writers of the books we are considering all seem to be experts in their field and have between them taught some remarkable pianists. So we turn with confidence to their writings, expecting to find them in general concord, and their discussions to be on the whole mere reinforcements of one another's ideas.

Suppose we look first at a very simple point, namely that of whether the finger should accelerate the key all the way down to the keybed or apply a force to it for only part of the descent. Ching writes categorically that the only sensible thing to do is to drive the key into the keybed. He is supported in his view by Schultz. Matthay and Gat, however, declare that this produces dreadful results and must at all costs be avoided.

Rather disturbed by this lack of unanimity over such a basic question, suppose we turn to the playing of a typical octave passage. Gat recommends the upward and downward movement of both forearm and upper arm, with the wrist relaxed. Ching's method is to oscillate the upper arm backwards and forwards whilst moving the forearm up and down, but keeping the wrist stiff and the elbow angle at 90 degrees. Schultz advocates a movement of the hand only; Matthay does likewise, but with the participation of the fingers and with the elbow at about 135 degrees. Fielden describes a technique where the wrist oscillates at half the frequency of the octave passage, and it is not quite clear what Breithaupt is driving at.

At this point the pianistic researcher might well stop and wonder, "If this is what happens when a fundamental point is at stake, what will things be like when a complicated action is under discussion?" His fears are entirely justified, for a deeper perusal of the books under review reveals an extraordinary diversity of proposed techniques.

This thesis is an attempt to examine technique from a firm scientific foundation, and so the next two chapters will be devoted almost entirely to a discussion of the basic biomechanics of the arm. Modern computer simulation techniques will be used to illustrate some of the arguments; perhaps this is the first time that piano playing has been studied with a computer.

3

THE PHYSIOLOGY OF THE ARM

3.0 INTRODUCTION

It is the purpose of this chapter to collect biomechanical data in preparation for Chap. 4, which deals with simulations of the arm. The data available in the literature is by no means complete, and so the data presented here is rather fragmentary. Actually, physiologists seem to have spent more time studying the action of the elbow than that of the shoulder, wrist or fingers (Vredenbregt and Koster, 1967), which is not really surprising as the elbow is about the simplest joint in the body. In view of this, this chapter will concentrate on the elbow and apply the information gained on it to the other joints in the arm, using a certain amount of extrapolation.

3.1 ANATOMY OF THE ARM (Gray, Wilkie(1950), Basmajian(1967))

The skeleton of the arm consists of one bone in the upper arm and two bones (to allow rotation) in the forearm, with the wrist and hand forming a complex of small jointed bones. The skeleton is covered with muscles which are capable of pulling the arm through a wide variety of movements. It is convenient to consider the muscles of the body divided into functional groups. These groups are almost invariably arranged in complementary pairs to give reciprocal movement, e.g. one group of muscles raises the forearm and another group of muscles lowers the forearm. These pairs are known as "antagonistic" or "synergistic" pairs of muscle groups.

It is generally recognised that there are three types of muscle : (1) Skeletal (voluntary) muscle, (2) Visceral (involuntary or smooth) muscle, and (3) Cardiac muscle. As the arm is a limb, its muscles are entirely skeletal. Skeletal muscles are made up of two types of fibres : (1) red fibre which is used for temporary, powerful actions (2) white fibre which is used for the lengthy maintenance of force. In some animals, the skeletal muscles are made up either of red or of white fibres, but in man, the muscles are composed of both types of fibre mixed together.

Skeletal muscles are attached at each end to points on the skeleton. If the force exerted has to be transmitted to a point some distance from the muscle, then the muscle is connected to it by a"tendon", which is a tough, virtually inelastic cable.

The boundary conditions of movement are determined by sets of tough fibrous tissues (similar to tendons). Thus the points where the bones join are provided with tissues to cushion the joint (to prevent fracture on impact) and to confine the joint to its normal range of turning (to prevent dislocation). In addition, the tendons are guided round corners by tissues arranged as sheaths.

Each muscle is controlled by the nervous system. Roughly speaking, a series of electrical impulses is sent to the muscle along the nerve, and the resulting amplitude of the force developed by the muscle depends on the frequency (not the amplitude) of the signals. Thus the muscle can develop a force which varies from zero to its maximum force. The muscle is equipped with sensory devices which send back information to the brain as to the amount of force in the muscle and its displacement. (One would guess that this feedback is not strictly necessary, but of course performance is almost always improved by the addition of a feedback loop).

3.1.1 The Muscles of the Arm (Gray, Schultz)

There are several muscles packed round the shoulder and it is difficult to understand their individual functions, as they are arranged in a complex way. However, it is clear that they have two main functions : firstly, to rotate the upper arm both backwards and forwards, and up and down; secondly to stabilise the shoulder so that it provides a firm base for arm movements.

The muscles of the elbow are arranged more simply and will be considered in some detail. The forearm is lowered by two muscles, the triceps and the anconeus. They lie along the back of the upper arm and are attached to the forearm where it protrudes at the back of the elbow. The forearm is raised by five muscles whose names and typical positions are given in the following table (Wilkie, 1950), where the first length given is the distance from the elbow to the point of connection on the forearm and the second length is the distance from the elbow to the point of connection on the upper arm (both are in metres)

Pronator teres	0.114	0.014
Extensor carpi radialis	0.221	0.035
Brachialis	0.034	0.100
Biceps	0.045	0.283
Brachioradialis	0.209	0.086

The right forearm is twisted clockwise by the biceps and the supinator, and anticlockwise by the pronator quadratus and the pronator teres. Thus some muscles perform more than one function, and there is some controversy over exactly what happens during a given movement.

The muscles which raise and lower the hand are situated in the forearm, rather near the elbow, and are attached to the wrist by quite long tendons.

The fingers are operated by a fascinating set of muscles. Fig.3.1.1.1 shows diagrammatically the raising and lowering muscles of one finger. The third phalanx of the finger (i.e. the end segment) is lowered by the flexor digitorum profundus, AB, the second phalanx by the flexor digitorum sublimis, CD, both of which are situated in the forearm. The first phalanx is lowered, relative to the hand, by the lumbricalis, EF, which is situated in the hand. The finger is raised by the extensor digitorum communis, XY, which lies in the forearm, and is attached to the second and third phalanxes. However, although each finger is equipped with individual lowering muscles, this is not true of the raising muscle. In fact there is a "common user" arrangement, as shown in Fig.3.1.1.2, with the extensor digitorum communis lifting all five fingers and two individual muscles, the extensor minimi digiti and the extensor indicis, raising the fifth and second fingers respectively. Whether this extraordinary arrangement is the most efficient is highly debatable. A little

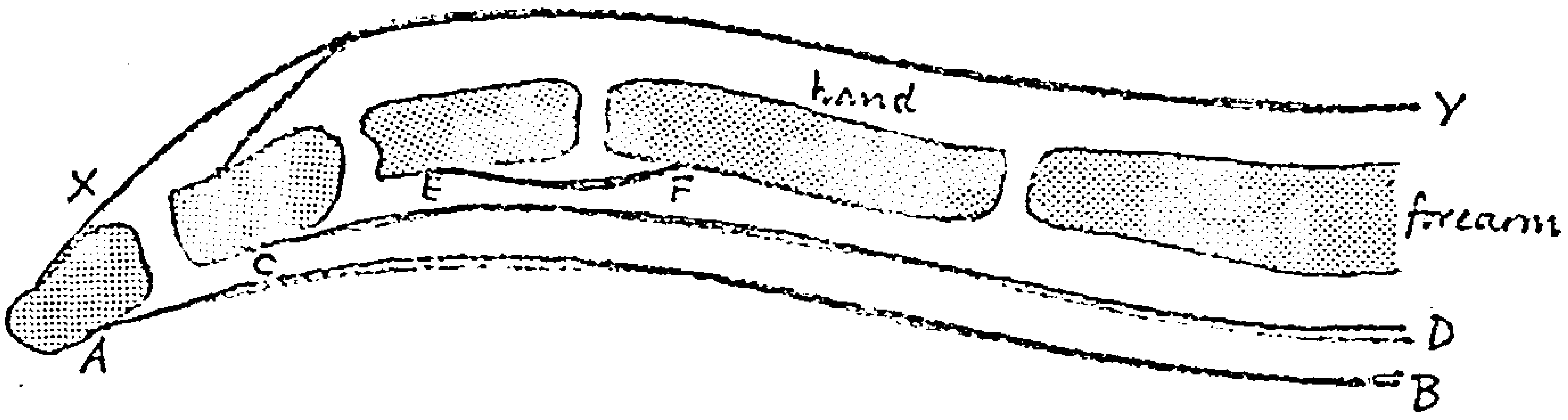


Fig. 3.1.1.1. Finger muscles

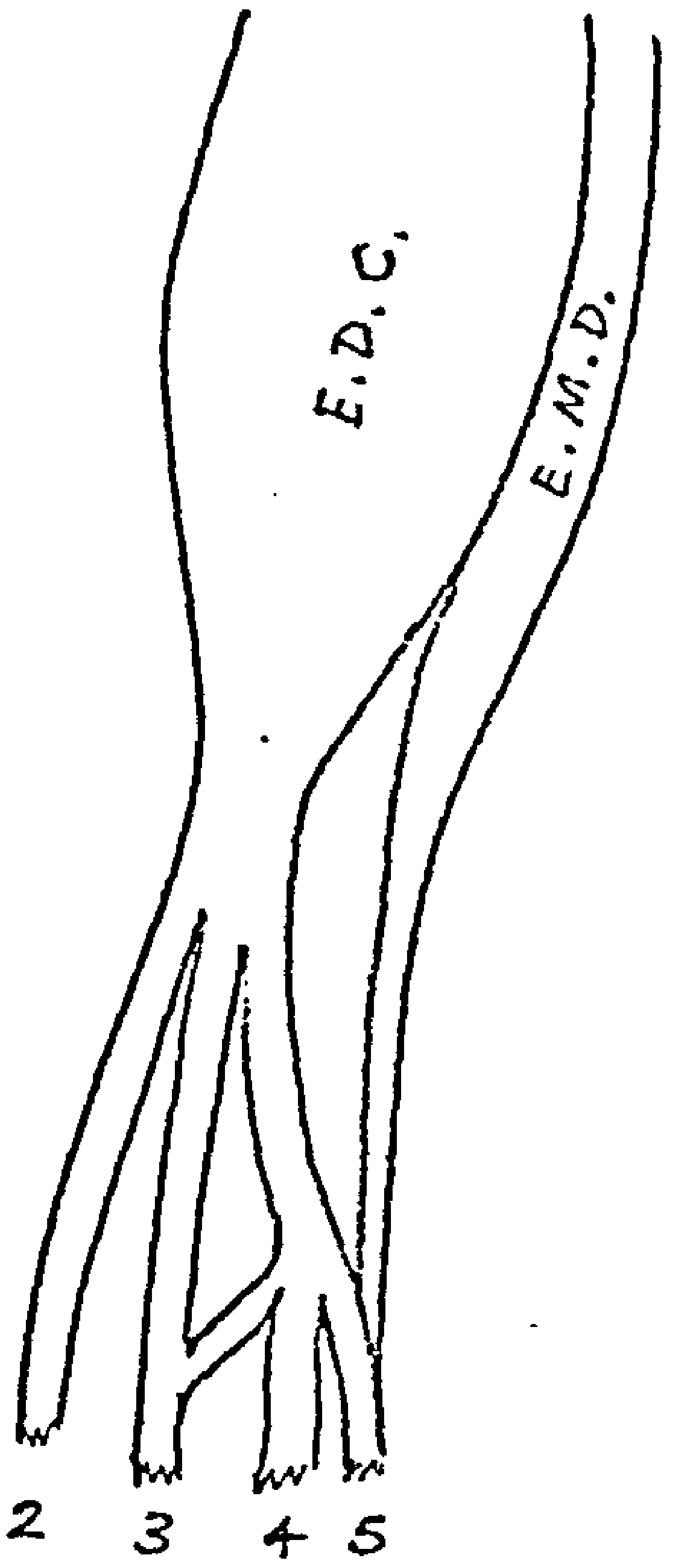


Fig. 3.1.1.2

Muscles and tendons of the fingers. The numbers indicate the fingers to which the tendons are attached.

thought reveals that almost any movement can be carried out, using the correct combination of muscles, and clearly the hand is well equipped for a variety of powerful gripping actions, but from the point of view of the pianist, the interdependence of the raising tendons of the third and fourth fingers is unfortunate.

The remaining muscles of the arm consist of muscles to move the hand sideways, muscles to move the fingers apart and a set of eight muscles for manoeuvring the thumb.

3.2 FUNCTIONS OF THE MUSCLES

In past times, anatomists had to discover the functions of individual muscles of the body by guesswork and common sense, their conclusions often being debatable. In the last twenty or thirty years, however, a new technique of studying muscular behaviour has arisen, namely the recording of muscular activity by electromyography(henceforward termed "EMG"). This consists of inserting a very fine wire into a muscle and picking up the very small electrical signals always present in a muscle, which are then electronically amplified. When the muscle is activated by the brain a characteristic trace is obtained.

Practically all the EMG investigations which have been carried out have been summarised in a comprehensive work by Basmajian (1967), who rather airily writes

> "It is not enough to estimate by classical methods" (i.e. mechanical, etc.) "what a muscle can do or might do. Electromyography is unique in revealing what a muscle actually does at any moment during various movements and postures. Moreover, it reveals objectively the fine interplay or co-ordination of muscles; this is patently impossible by any other means"

All the same when Basmajian comes to look at simple flexion of the elbow joint, he can find nothing but a mass of inconsistent results - so much for seeing what the muscles actually do. In fact biomechanical study and EMG results are nicely complementary; the former provides a physical understanding, the latter provides a verification of theories.

Basmajian makes considerable reference to a classification of skeletal muscles introduced by Mac Conaill (1946, 1949). Mac Conaill divides muscles into two groups : "shunt" muscles and "spurt" muscles. A spurt muscle is one which acts at right angles to a moving bone; a shunt muscle is one which acts along the moving bone. (Fig.3.2.1) Mac Conaill's theory is that the spurt muscle provides the acceleration along the curve of motion and hence is used in moving the bone, and the shunt muscle provides the centripetal force and hence stabilises the joint. To take an example, in the elbow the biceps and brachialis are chiefly spurt muscles while the brachioradialis is chiefly a shunt muscle. This theory will be examined in the next chapter.

3.3 BIOMECHANICS OF THE ARM

The mechanical properties of the skeleton of the arm are quite straightforward. Each link of the skeleton is tough and rigid, and the links are connected by simple hinge or ball-and-socket joints. The whole mechanism can therefore be successfully analysed by a set of simple equations based on Newton's Laws of Motion.

The frictional properties of the joints deserve a mention. Williams and Lissner (1962) discuss experimental work done in

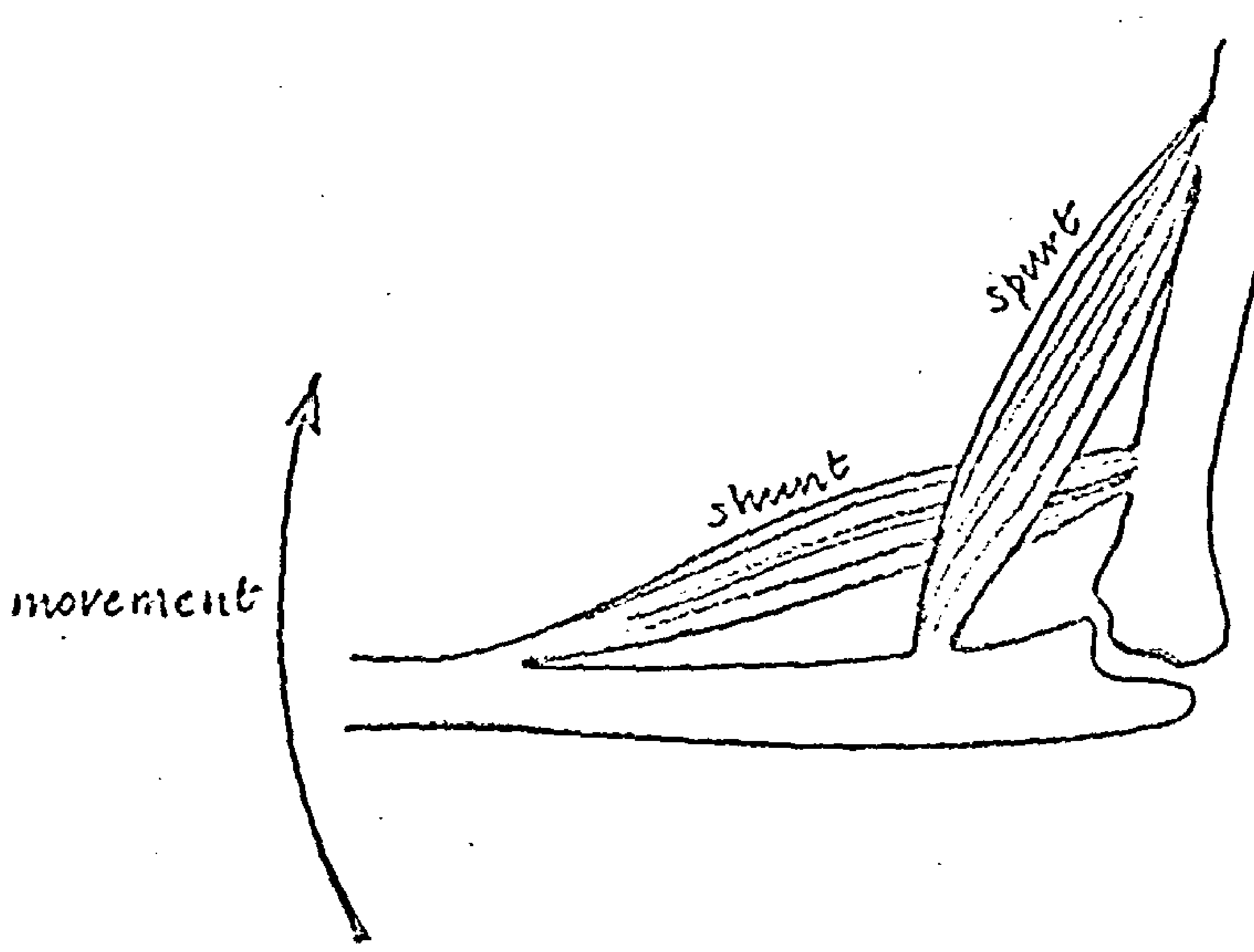


Fig. 3.2.1 Shunt and spurt muscles.

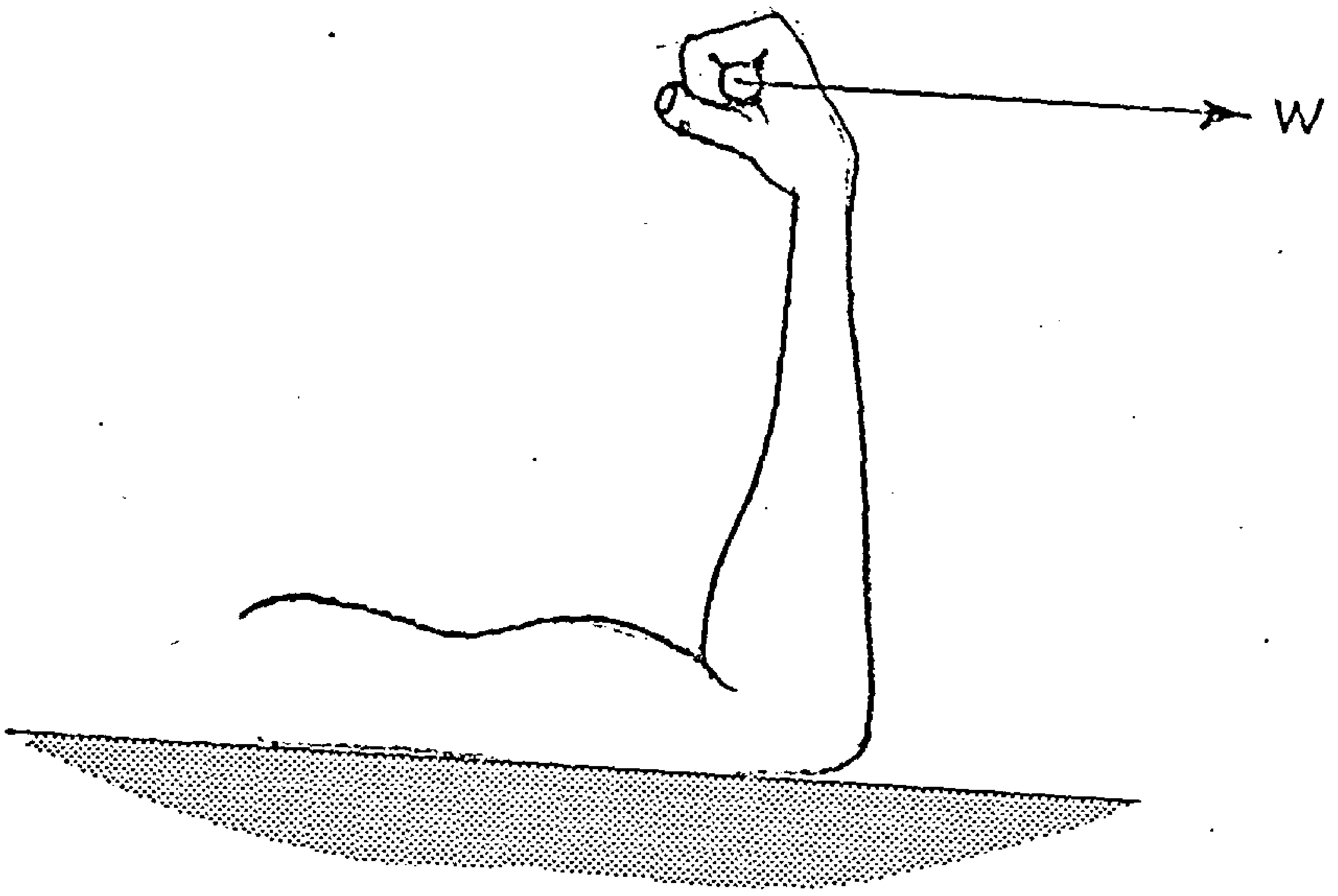


Fig. 3.3.1.1 Wilkie's Apparatus

this field and they remark on the extraordinarily low coefficient of kinetic friction of the average joint. One investigator gives a value of 0.013 for the coefficient, others give around 0.020. (By comparison, Goodman and Warner (1963) give the coefficient of limiting static friction of hard steel surfaces lubricated with molybdenum disulphide as 0.1). Williams and Lissner calculate that their values give, typically, an extra load at the joint of about 1% of the load being carried.

Whilst the equations of the skeleton present little difficulty, a mathematical statement of muscular action can be quite problematic. The standard account of muscle mechanics seems to be that of Wilkie (1950). As the properties of muscles form a central part of this thesis, Wilkie's paper is now examined in detail.

3.3.1 A Summary of Wilkie's Paper (1950)

Wilkie's article is long and difficult to understand. The difficulty arises partly because of the subtlety of the arguments involved, and partly because of the curiously inverted way in which the analysis unfolds. Instead of visualising the properties of muscles as mechanical components, Wilkie describes them by rather complicated equations and develops a series of what might be called "equivalent effects". To give one example, when he is considering a mass-viscosity system, he ignores the mass, without making this clear, and, having got the wrong answer, speaks of the inertia term as being a "correction". Furthermore, although Wilkie is studying the rotation of the elbow when acted on by five muscles situated on the forearm and upper arm, his equations are worked out to represent muscle properties as he puts it "localized at the hand".

Rather than attempt a precis of the paper, I have here completely reorganised the analysis using the idea of active and passive mechanical components.

It is the aim of Wilkie's paper to study the mechanical action of a typical muscle group, and for this purpose he chooses the muscles of the elbow which raise the forearm. Wilkie's work is the first done in vivo and naturally it is difficult to measure muscles in a living person, as one can do no sort of dissection.

Wilkie takes measurements when the arm is held as in Fig.3.3.1.1 with the hand gripping a bar which is coupled to a constant horizontal force, W. The wrist is always kept rigid and in all cases the subject makes a maximum effort. Wilkie produces the following set of results (the angle $\theta(t)$ is the interior angle of the elbow) :-

1. The arm starts from rest from an angle θ of 140°. The horizontal velocity of the hand $V(t)$ is measured at the instant when $\theta = 80°$. This velocity, V_{80} , is plotted against W. (Fig.3.3.1.2)

2. Keeping the same initial conditions and stopping the arm mechanically at $\theta = 75°$, $V(t)$ is measured and plotted against time, t , with W as parameter. (Fig.3.3.1.3)

3. Holding θ constant by mechanical means the force exerted W (measured by strain gauge) is plotted against t (Fig.3.3.1.4, upper curve). Wilkie does not give the value of θ but it is probably about 90°.

4. This experiment is the same as the third one, but an elastic cable of stiffness 1750N/m placed in between the hand and the load. (Fig.3.3.1.4, lower curve).

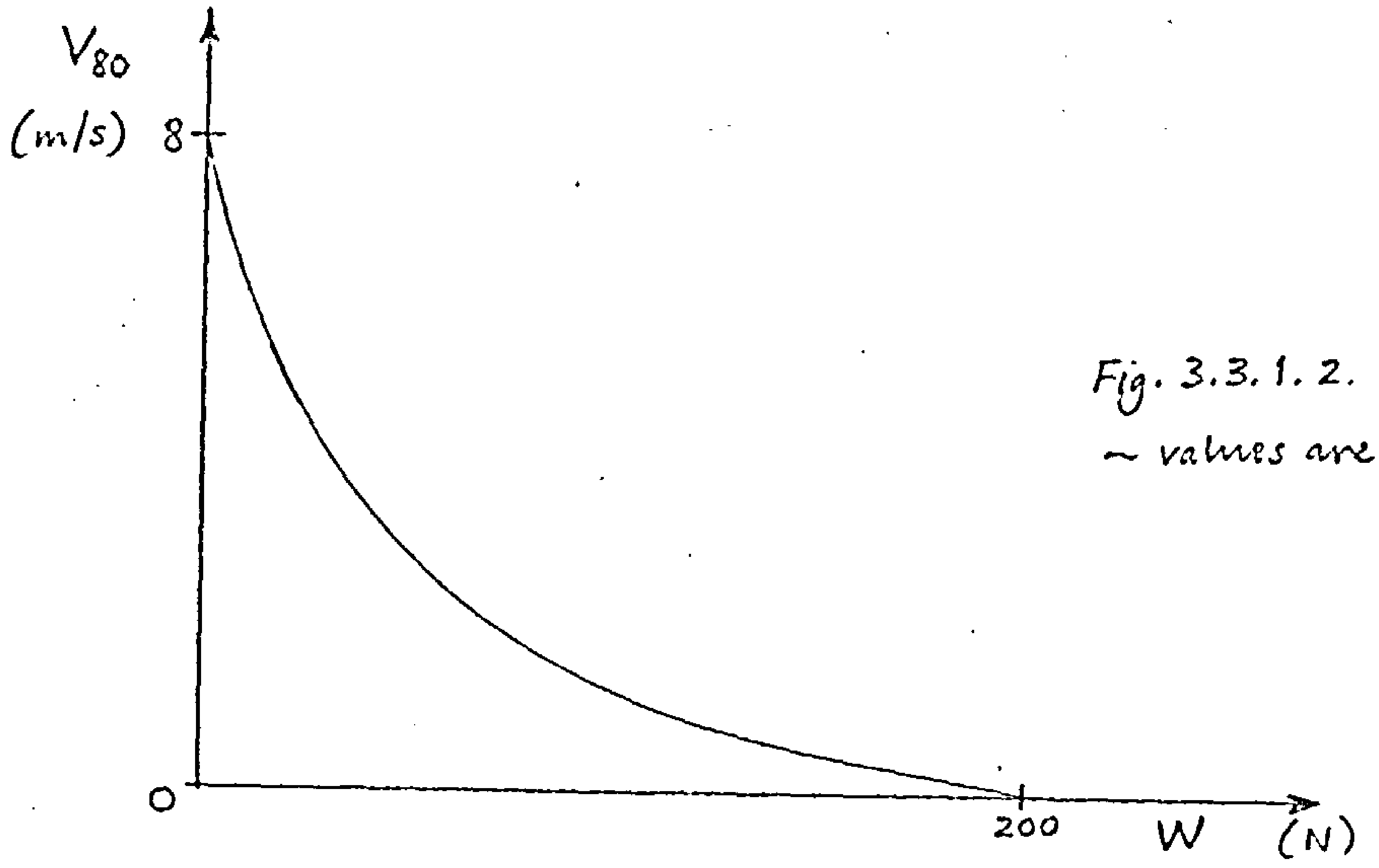


Fig. 3.3.1.2.
~ values are typical.

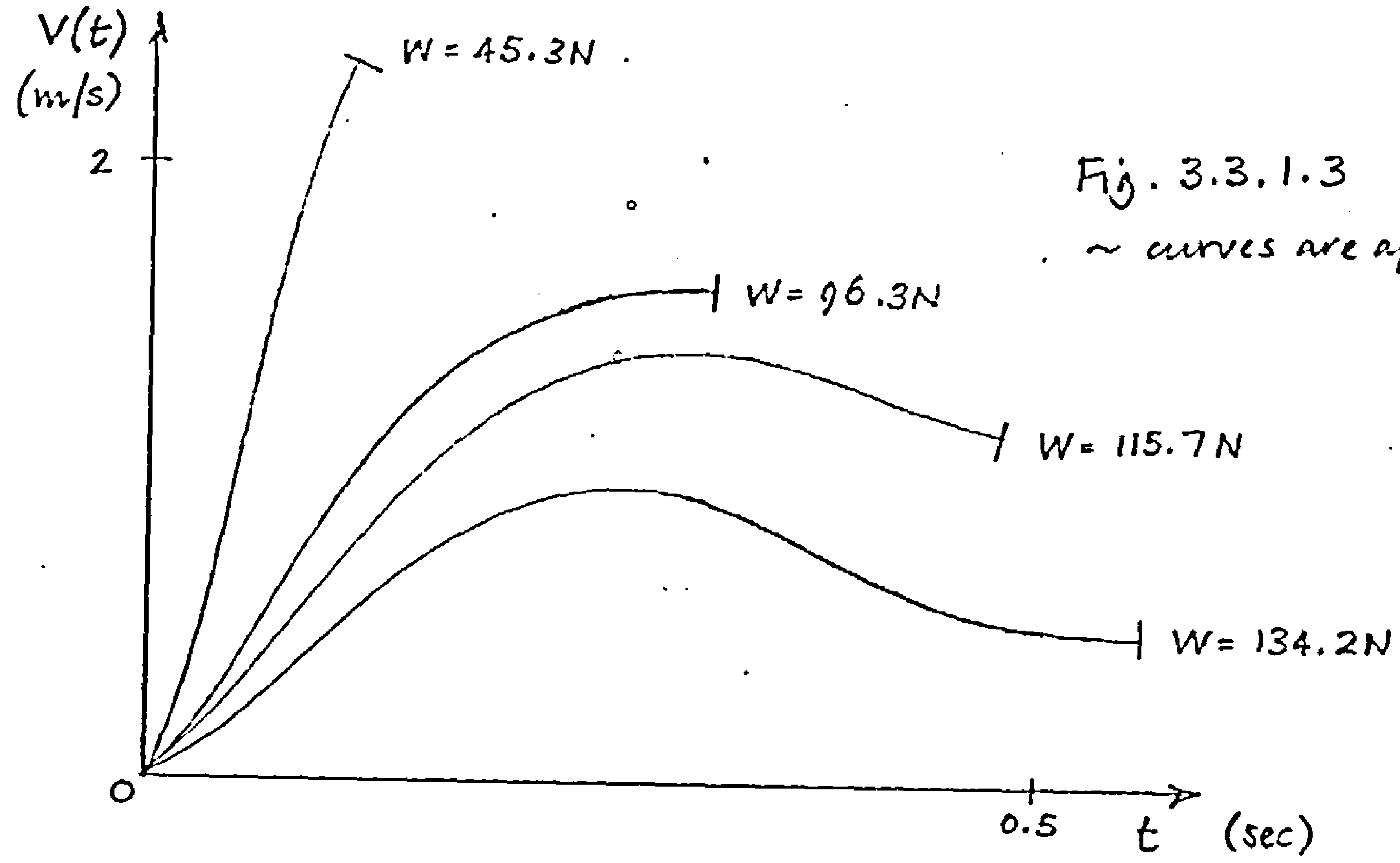


Fig. 3.3.1.3
~ curves are approximate

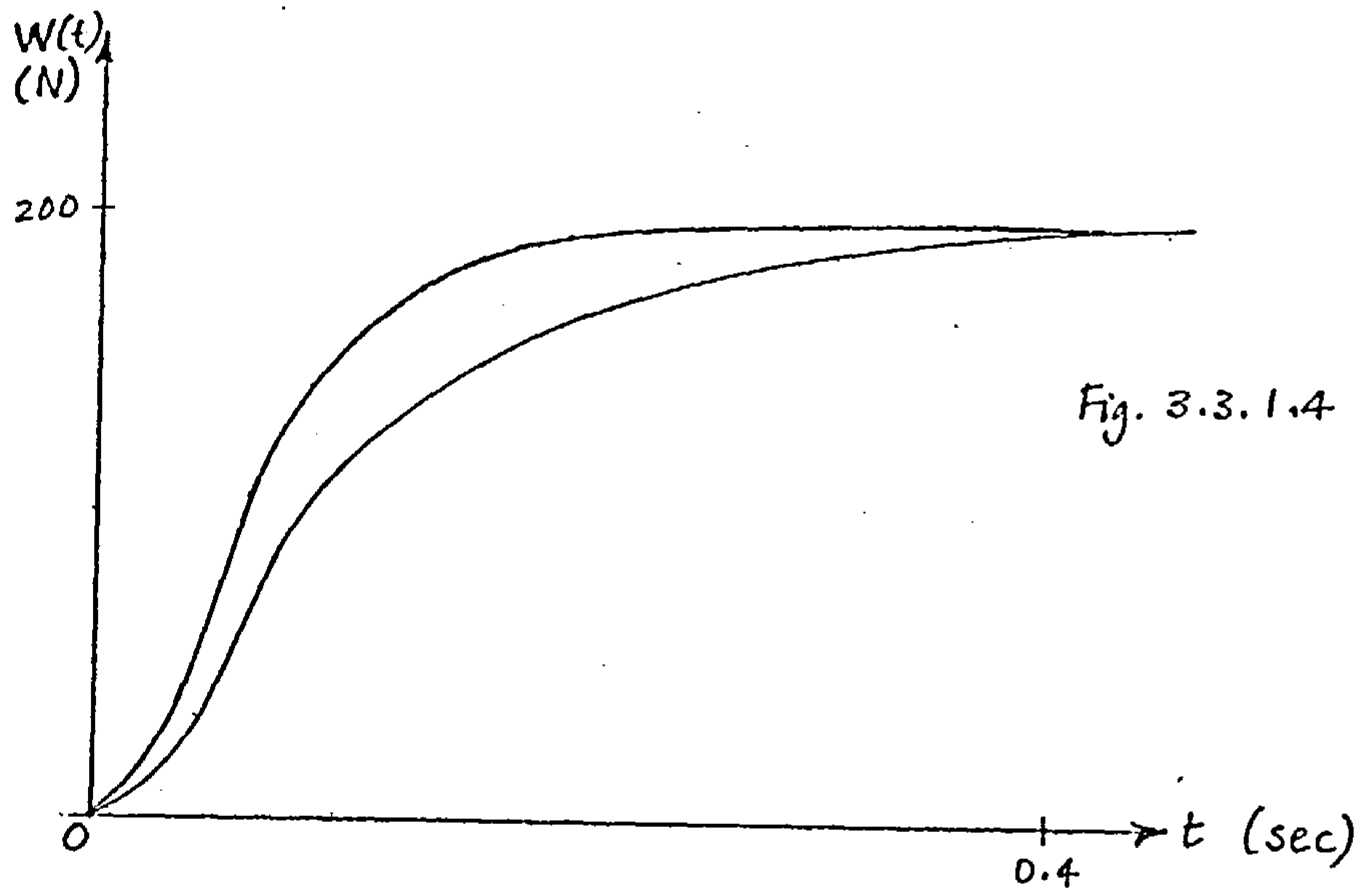


Fig. 3.3.1.4

The next section analyses these results.

3.3.2 Constructing a Model of the Elbow Joint Based on Wilkie's Paper

We know that a muscle exerts an inward-acting force between its extremities, tending to shorten the muscle. We know also that a muscle is operated by the nervous system which dictates what proportion of the maximum force shall be developed. If we assign the symbol F^M to the maximum force which it is possible for a muscle group to produce, and the symbol ζ $(0 \leqslant \zeta \leqslant 1)$ for the fraction of F^M which is actually developed, then we can represent a muscle group under static or near-static conditions by an ideal force-producing element of magnitude ζF^M, where F^M is constant and inward-acting, and ζ is a function of time, t. (Fig.3.3.2.1). The muscle group will be considered to be "switched on" when $\zeta = 1$ and "switched off" when $\zeta = 0$. As this force element is ideal, the force developed is independent of the length of the element. This is analogous to an ideal current-producing element in electrical circuit theory which produces current independently of its voltage. The validity of such a simplification will be discussed later.

As this element represents a muscle group rather than a single muscle, it is a moot point as to where it should appear on a model of the arm. Wilkie takes his element as acting between the shoulder and a point 1/7 - way along the forearm from the elbow, but gives no reasons as to his choice of the factor 1/7. In view of the dimensions of the muscle lever arms given in Sec.3.1.1, this seems rather too far removed from the elbow to me. Accordingly in this thesis the muscle element will be considered to be attached rather closer to the elbow. Anticipating Sec.3.6, the distance

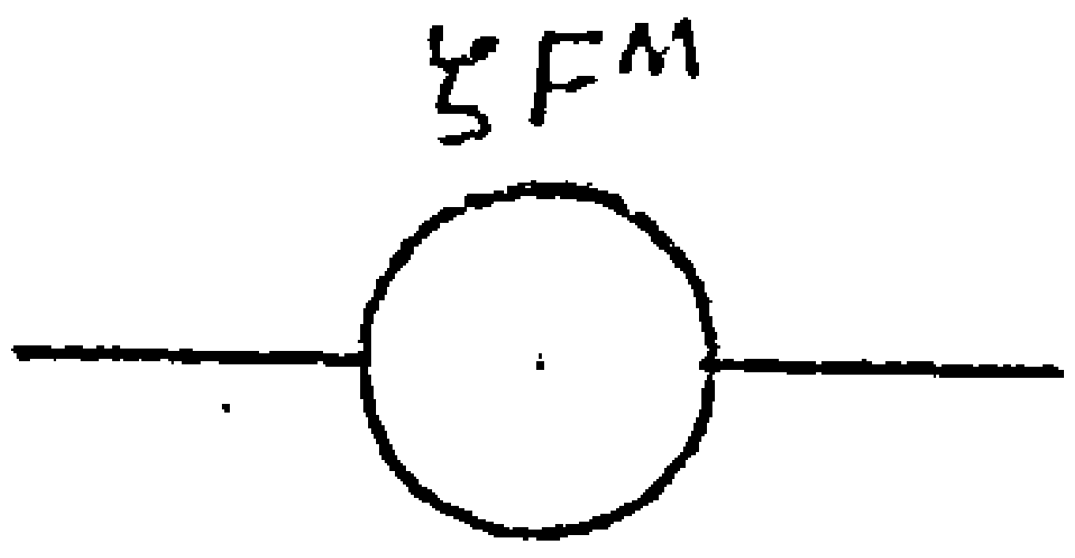


Fig. 3.3.2.1

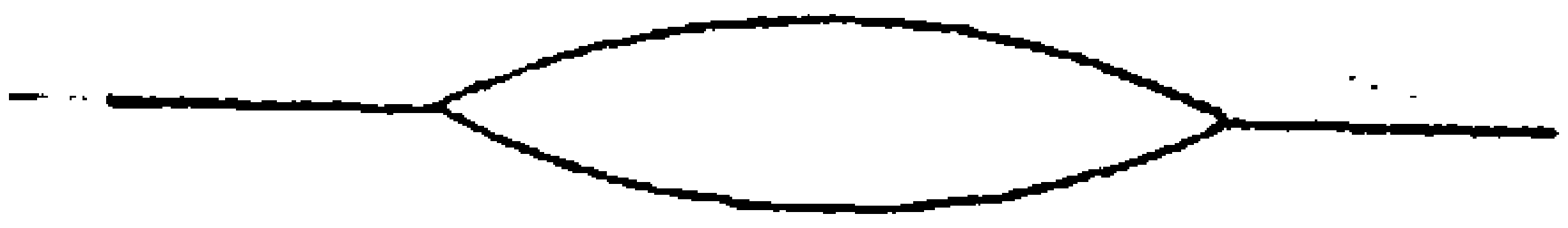


Fig. 3.3.2.2

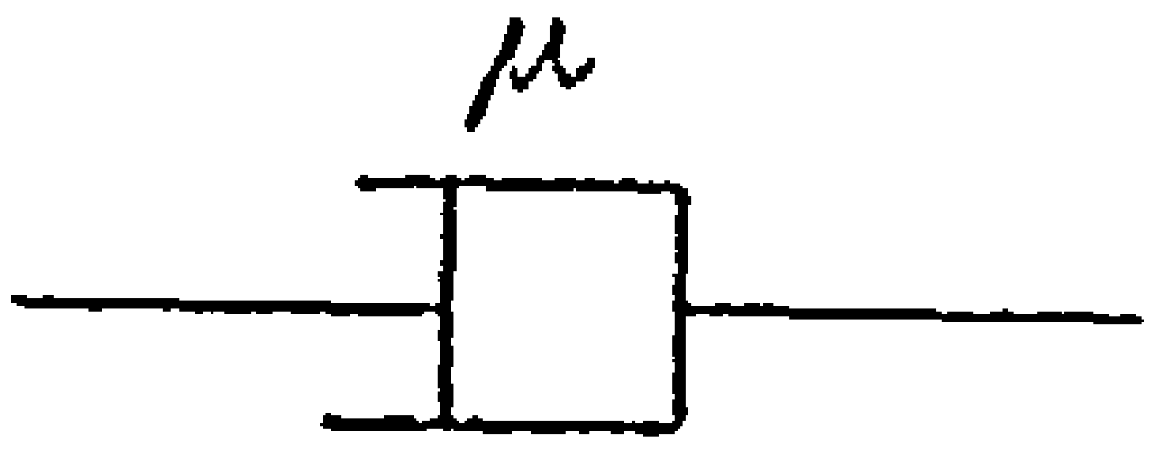


Fig. 3.3.2.3

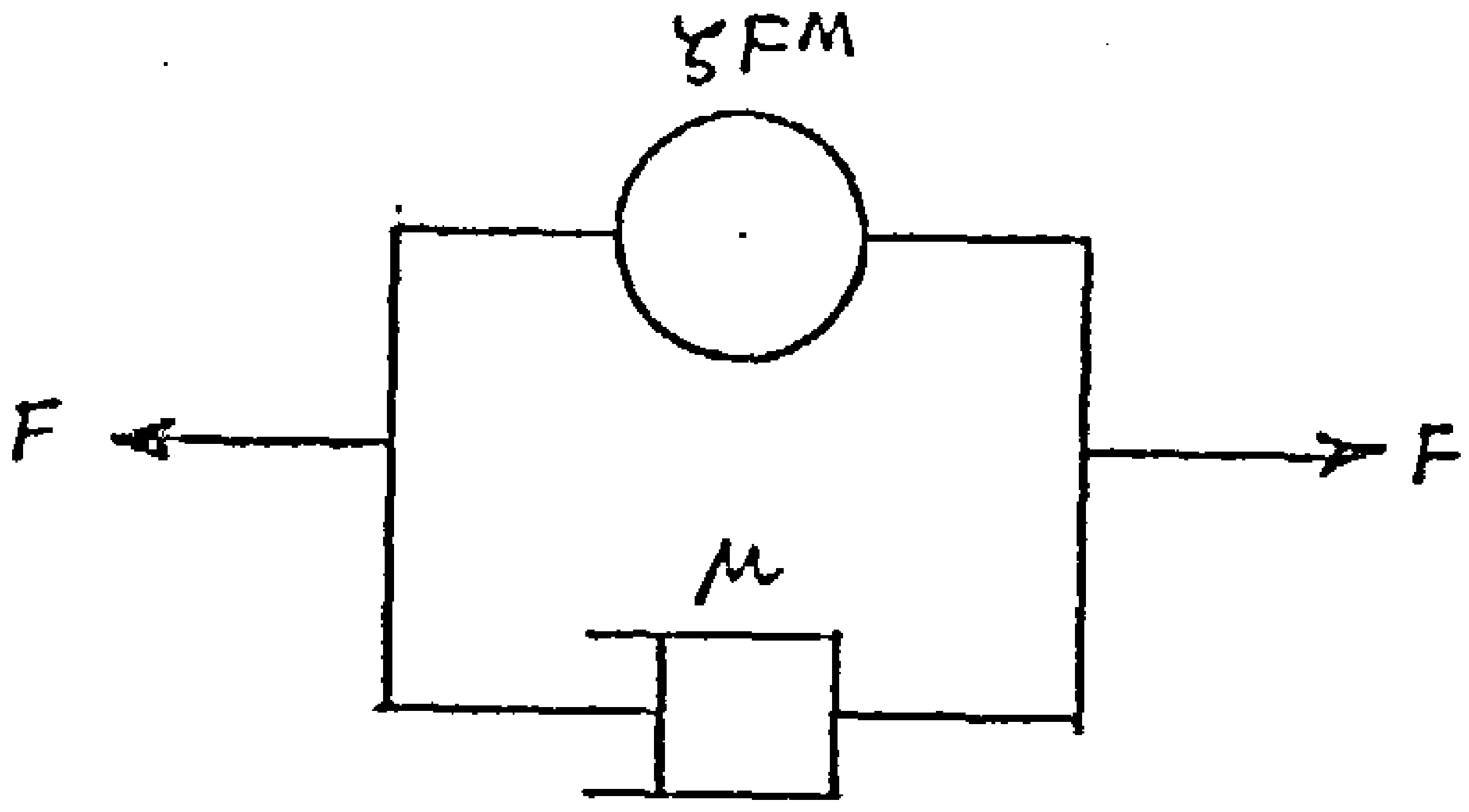


Fig. 3.3.2.4

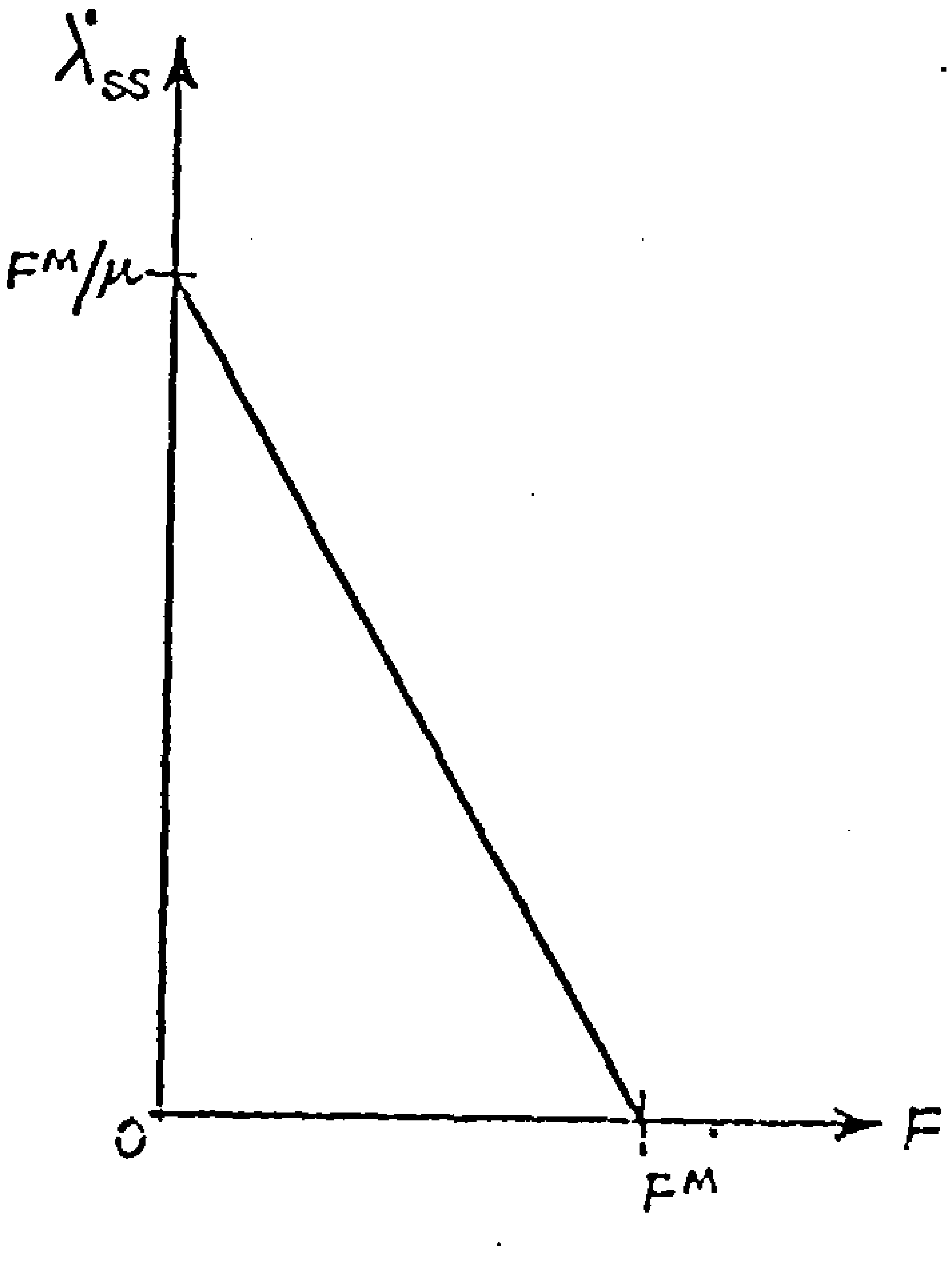


Fig. 3.3.2.5

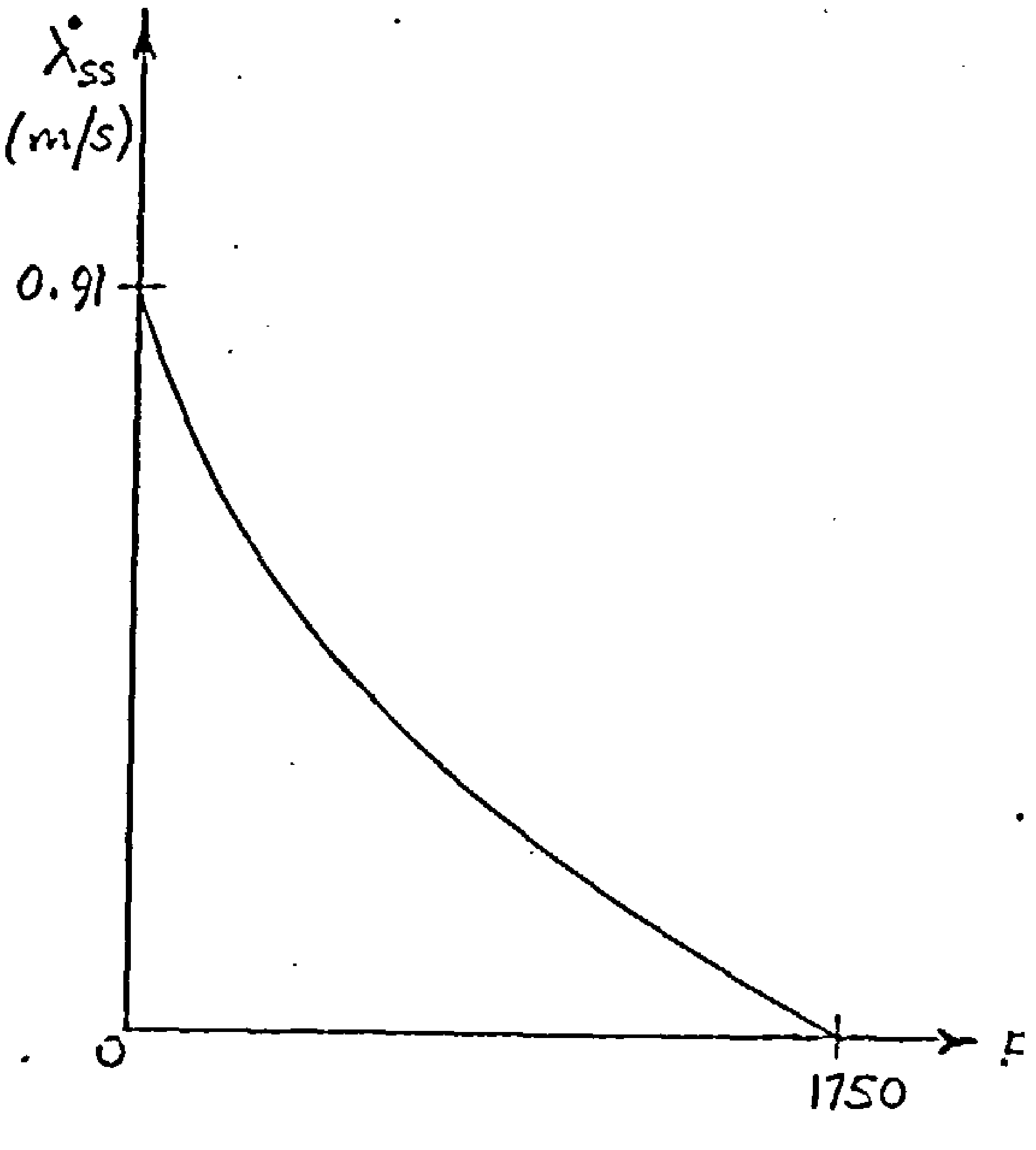


Fig. 3.3.2.6

from the elbow to the muscle element will be taken as 0.04 metres, and the length of the forearm from the elbow to the grip of the hand as 0.35 metres.

In this representation of the elbow muscles, the action of five muscles has been represented by one element. In future this element will be referred to as a "single equivalent muscle" (SEM) and indicated by the symbol of Fig.3.3.2.2.

Wilkie's first curve shows the muscles under dynamic conditions. The muscle group is loaded by the applied force, W, and by the inertia of the forearm about the elbow (and, as Wilkie produces W from a hanging weight, the inertia of this weight also acts as a load). We can see from this curve that there is probably considerable viscosity present in the muscle group. Suppose we take the length of the SEM to be λ and the actual loading of the SEM to be the force F. Now if we introduce a new element, that of a linear dashpot (Fig.3.3.2.3) of value μ (such that the applied force equals μ times the rate of its shortening) then we can more accurately represent our SEM as shown in Fig.3.3.2.4. The characteristic equation for this model is

$$\gamma(t)\,F^{M} - F(t) = -\mu\dot{\lambda}(t) \qquad (3.1)$$

If $\gamma(t) = 1$ (which is always the case in Wilkie's measurements), then when the rate of shortening reaches a steady state, $F(t)$ becomes constant and

$$\dot{\lambda}(t) = \dot{\lambda}_{ss} = (F^{M} - F)/\mu \qquad (3.2)$$

This is shown in Fig.3.3.2.5

To check the accuracy of this model, Wilkie's curve of V_{80} versus W must be converted to a curve of $\dot{\lambda}_{ss}$ versus F. We can see from Wilkie's second curve that V_{80} is not quite a steady state velocity, and so the effect of the inertial terms must be allowed for. The estimation of these terms is by no means simple. Wilkie uses approximations and elaborate calculations and shows that the difference between V_{S0} versus W and the theoretical steady state velocity V_{SS} versus W is quite small. Now taking $\dot{\lambda}_{ss}$ = 0.04/0.35 times V_{SS} and F = 0.35/0.04 times W (these are slight approximations) we get the curve of Fig.3.3.2.6. By comparing this with Fig.3.3.2.5 we see that the viscosity of the real muscle group is nonlinear. We also see that our assumption of the existence of a viscous element was correct.

If the SEM can be represented as shown in Fig.3.3.2.4, then the muscle-arm-load system of Wilkie's first and second experiments can be represented as shown in Fig.3.3.2.7 (the shaded area is fixed in space). Of course the value of the inertial element, m, in reality is not constant, as it depends on θ, but Wilkie is able to show that between the angles of 70° and 110° the variation in inertia is only 13%. Now if the viscosity were linear and m constant over $75° < \theta < 140°$, then we would have a simple first-order system, and the graph of the velocity of the hand $V(t)$ versus t, with $\theta(0) = 140°$ and W as parameter, would be as shown qualitatively in Fig.3.3.2.7 remembering that $V(t)$ = 0.35/0.04 times $\dot{\lambda}(t)$.

Comparing this curve with Wilkie's experimental result (Fig.3.3.1.3) shows that in reality, even allowing for the nonlinearity of m, the muscle group does not behave as a first-order system, but more like a second-order system. Suppose, therefore, we now introduce another element, that of an ideal linear spring of stiffness κ (Fig.3.3.2.9), and add this to our SEM model as shown in Fig.3.3.2.10. The overall length of the SEM is still taken as $\lambda(t)$, but the decrease in length of the elements ζF^M

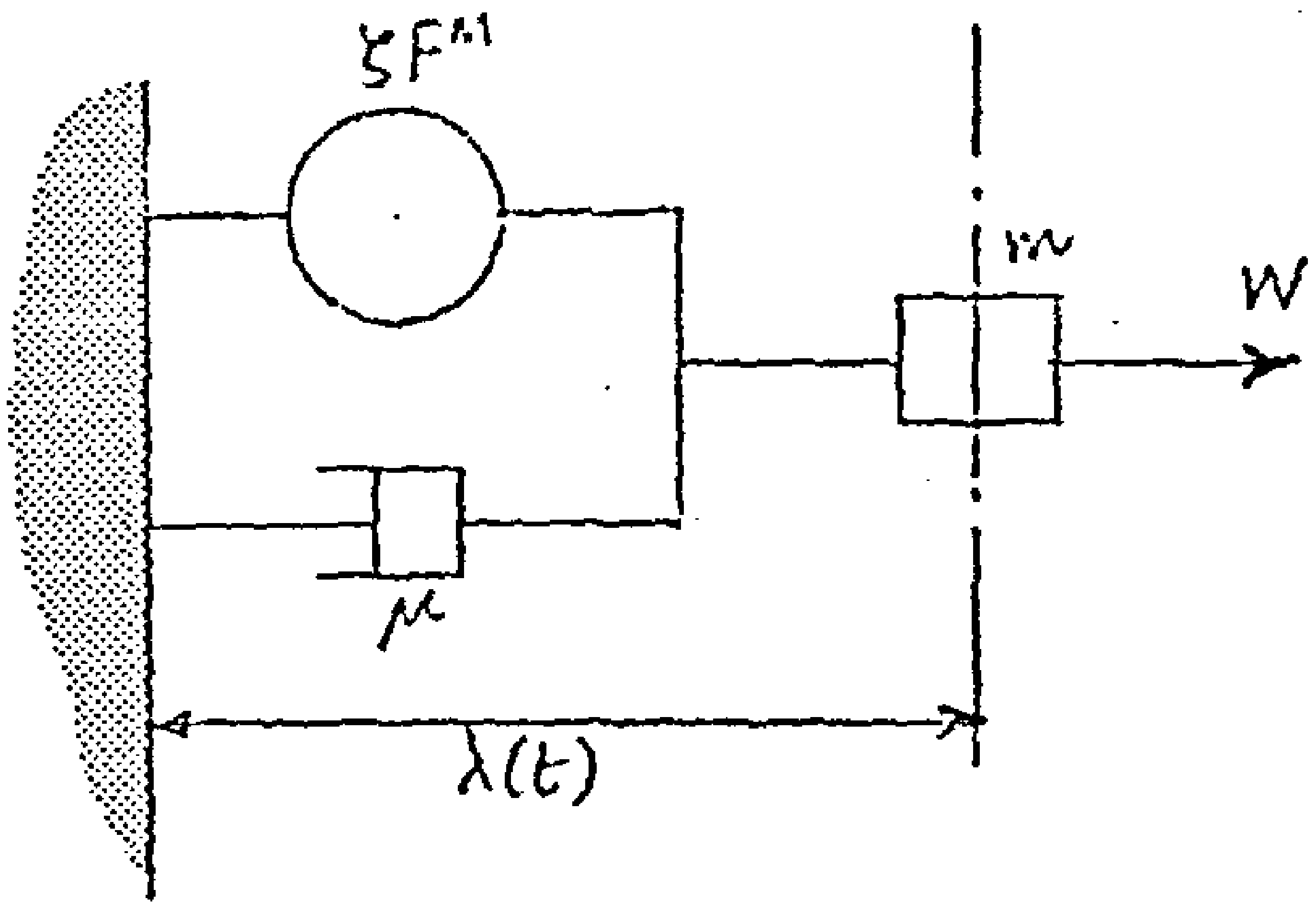


Fig. 3.3.2.7

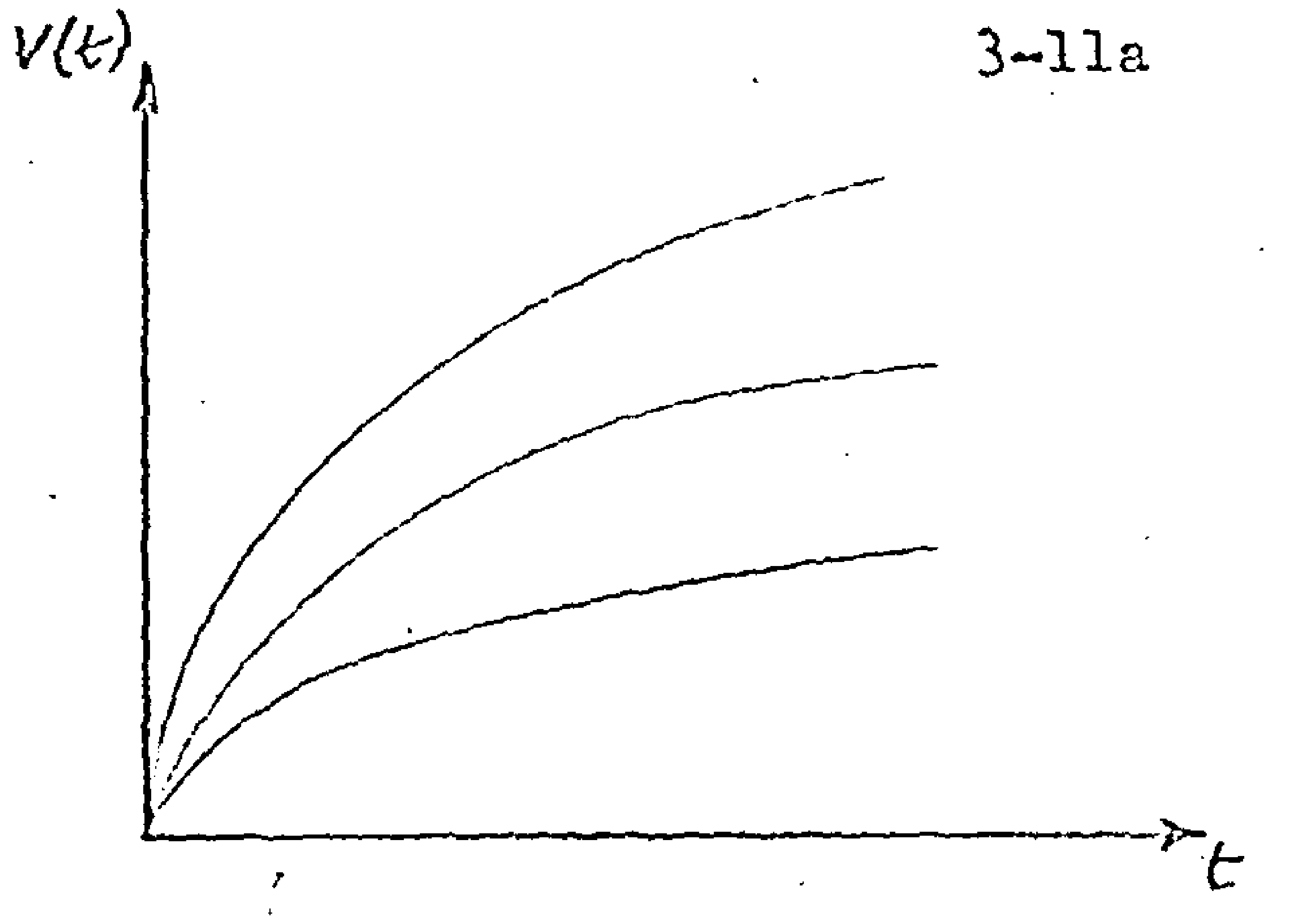


Fig. 3.3.2.8

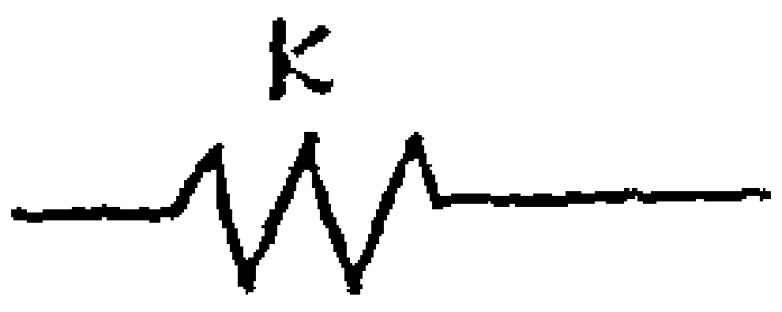


Fig. 3.3.2.9

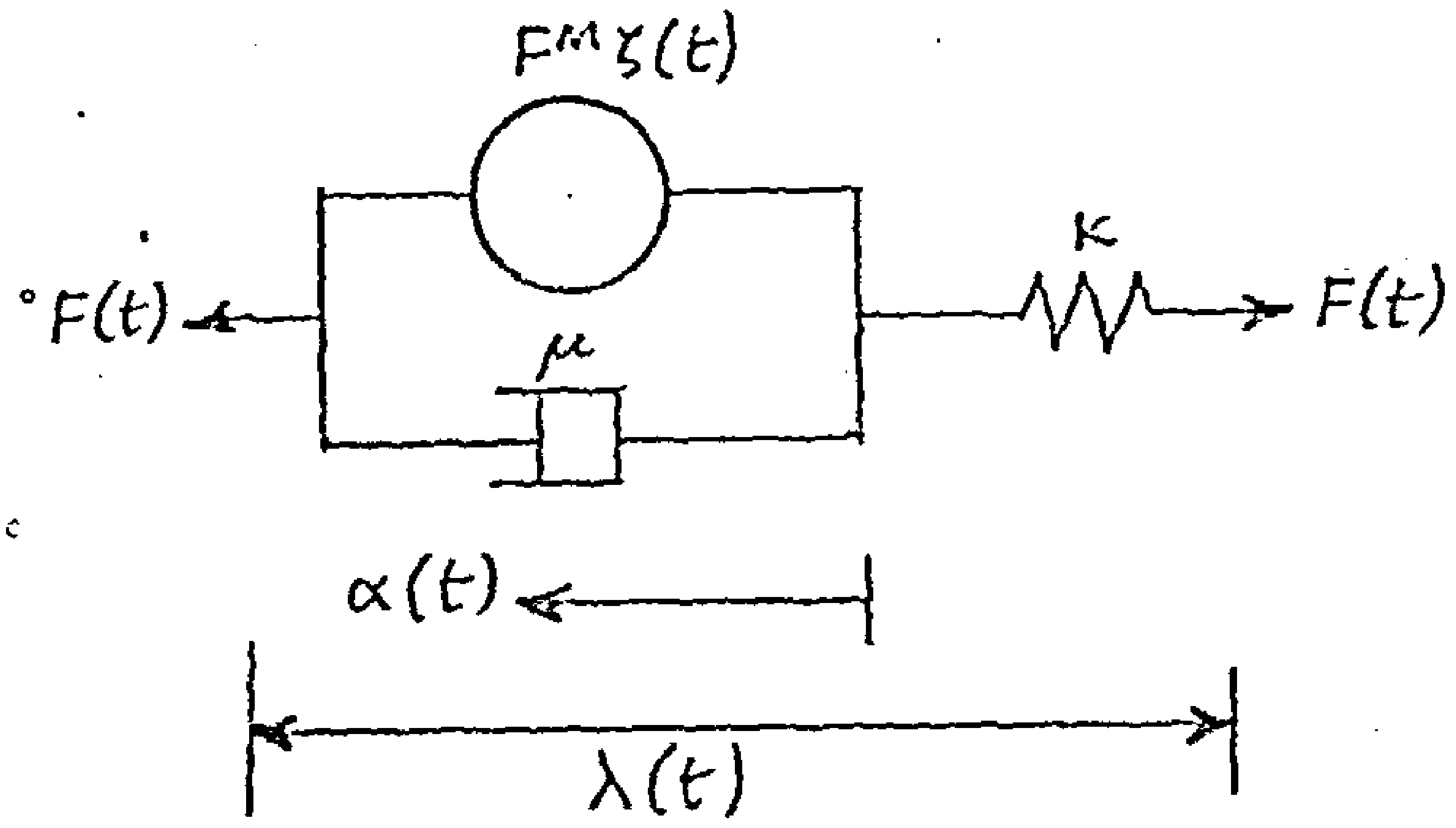


Fig. 3.3.2.10

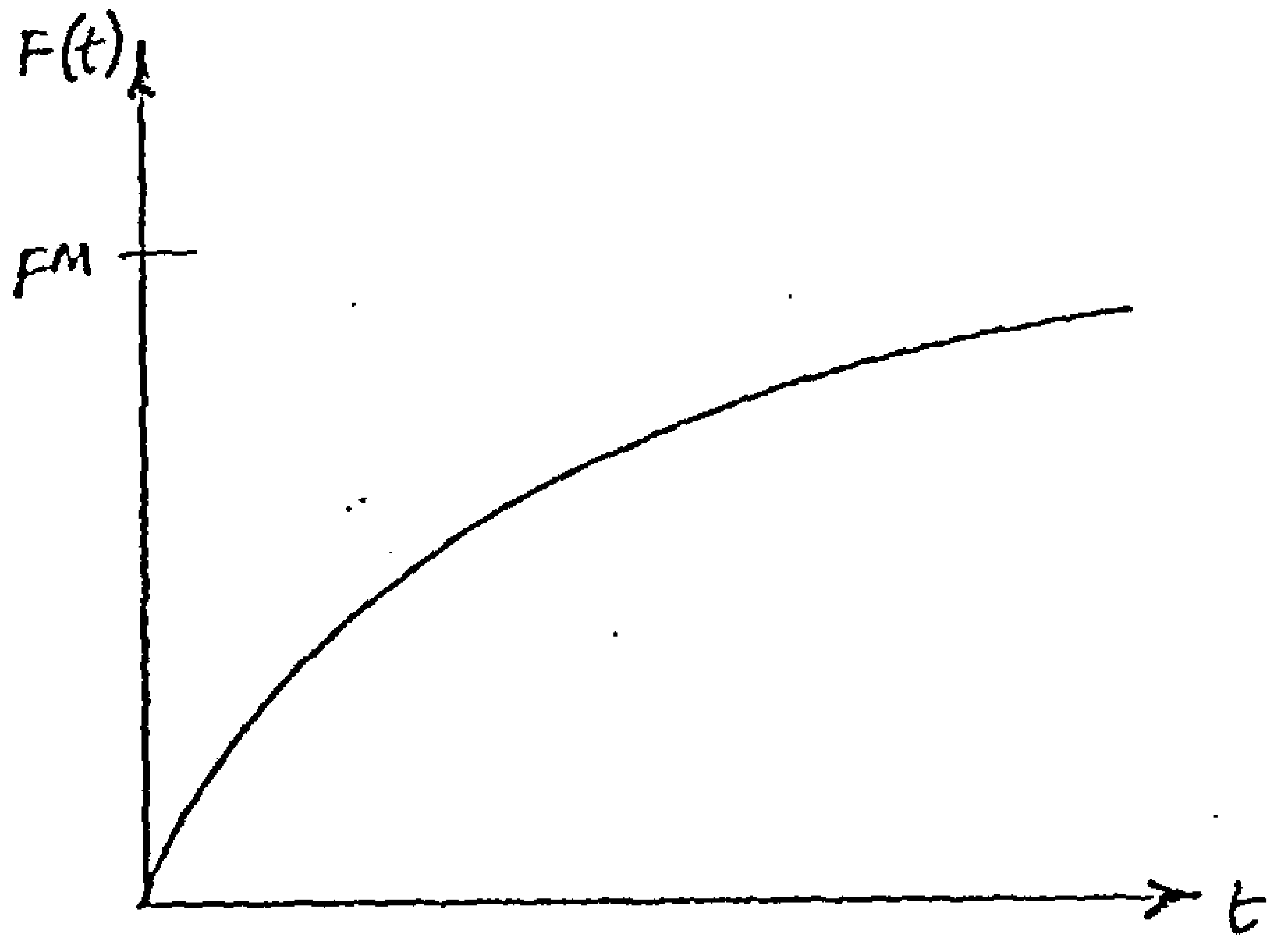


Fig. 3.3.2.11

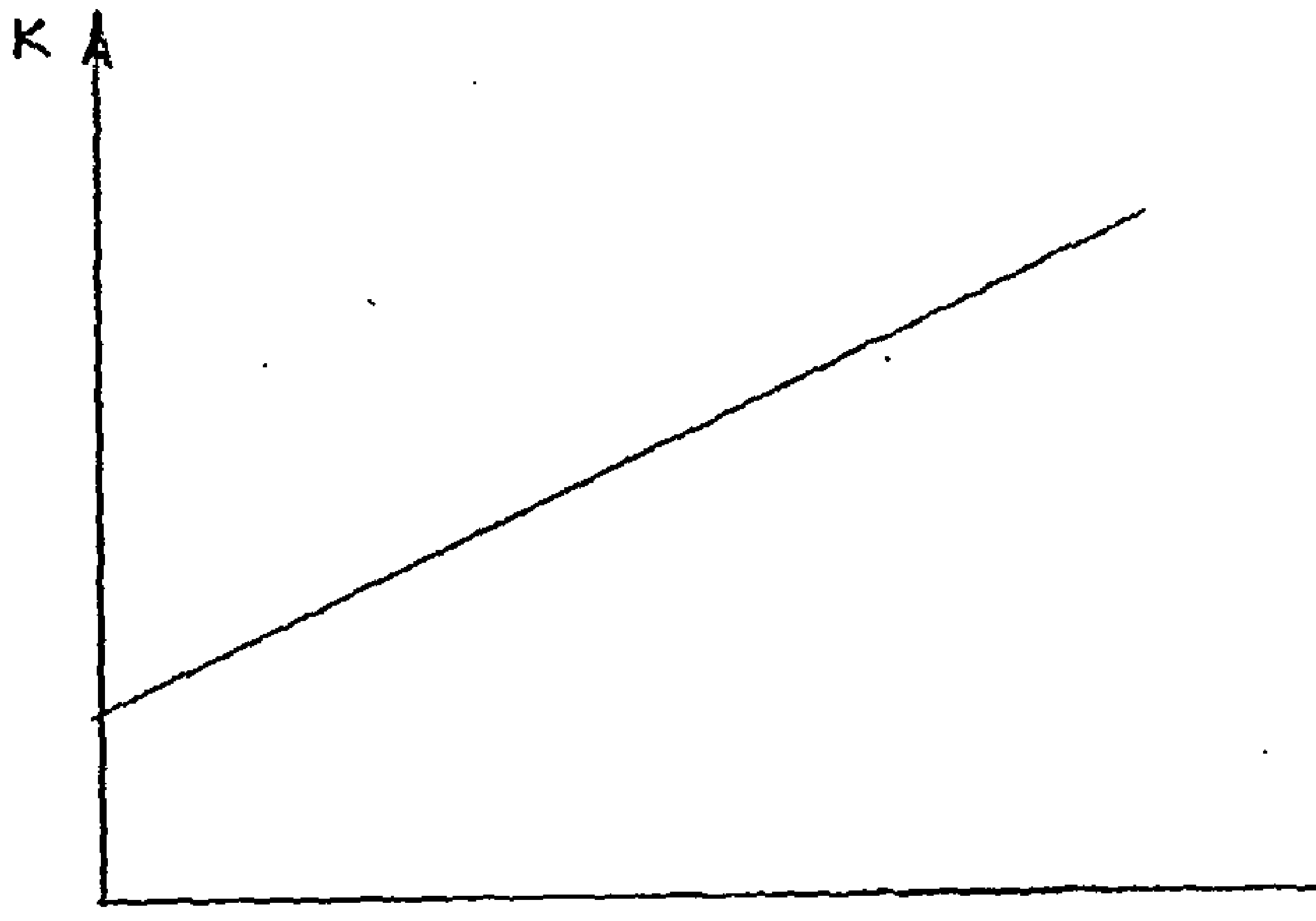


Fig. 3.3.2.12

~ various values.

and μ is now $\alpha(t)$. If we assign the symbol λ^0 to the unstretched length of the whole muscle, we have the conditions that when ζ and F are held at zero, $\lambda(t) = \lambda^0$ and $\alpha(t) = 0$.

The equations of the system are:-

Viscous element : $F^M \zeta(t) - F(t) = \mu \dot{\alpha}(t)$ (3.3)

Elastic element : $F(t) = \kappa \{ \lambda(t) - \lambda^0 + \alpha(t) \}$ (3.4)

Combined equation : $\dot{F}(t) = (\kappa/\mu)\{ F^M \zeta(t) - F(t) \} + \kappa \dot{\lambda}(t)$ (3.5)

The spring element can be given a value by Wilkie's third experiment. If we impose on our SEM model the condition that $\lambda(t) =$ constant, we have (from equ.(3.5))

$$F(t) + (\mu/\kappa)\dot{F}(t) = F^M \tag{3.6}$$

This gives a solution of $F(t)$ as shown qualitatively in Fig.3.3.2.11. Now the slope of this curve is given by $\dot{F}(t)$ and hence, if the slope of $F(t)$ is known, a value of κ can be found, and Wilkie's third curve provides such a slope. Wilkie produces a value of κ from his experiment, taking into account the non-linearity of μ, and gets κ as a function of F (Fig.3.3.2.12).

Wilkie's fourth curve is intended to provide confirmation of the proposed model of Fig.3.3.2.10. The point is that, although the model will give curves of $V(t)$ versus t which look similar to Fig.3.3.1.3, we cannot be sure which elements give rise to the curve, because if $\zeta(t)$ in reality where not a step function, but showed instead an initial rise from zero to unity with a rise time of the order of 0.2 sec., then the effect would be similar to that of a spring in series with the model. Accordingly Wilkie calculates the apparent value of the spring element when an elastic cable is placed in series with it, and obtains a curve almost identical to Fig.3.3.2.12, but about 1750 N/m higher. Thus the postulate of a series spring element seems to be correct. It is easy to see that if there is a spring element in series then this will show an apparent increase of 1750N/m, but, although Wilkie calculates the elasticity carefully, he does not explain clearly why this is sufficient proof.

3.3.3 Further Papers on Muscle Properties

In a later work (1956), Wilkie investigates the properties of an isolated frog's muscle. He gives the magnitude of force developed by the muscle, F^M, when $\zeta = 1$ and the length λ is held constant. His curve of F^M versus $\lambda - \lambda^0$ is shown in Fig. 3.3.3.1. We can see from this that a muscle cannot develop force successfully when it is below its rest length. (This statement applies to a single muscle, not a muscle group).

In a still later work (1958), Jewell and Wilkie postulate a further elastic element in their muscle model, this time in parallel. However, as they do not give any information on how this affects the human arm, this doubly-elastic model will not be taken up in this thesis.

So far, we have always been considering the muscle group under study to be fully stimulated, so that all the parameters correspond to the case where $\zeta = 1$. There is naturally no guarantee that the parameters remain the same when ζ is changed. In view of this, Bigland and Lippold (1954) have measured the viscosity of a muscle group (the thigh muscles this time) at different levels of stimulation, and the curves shown in Fig. 3.3.3.2 are derived from their results. We can see from this that, if the curves are linearised by joining their endpoints, the viscosity, as ζ varies, is not constant - in fact, it is clear that the viscosity is virtually proportional to ζ. If

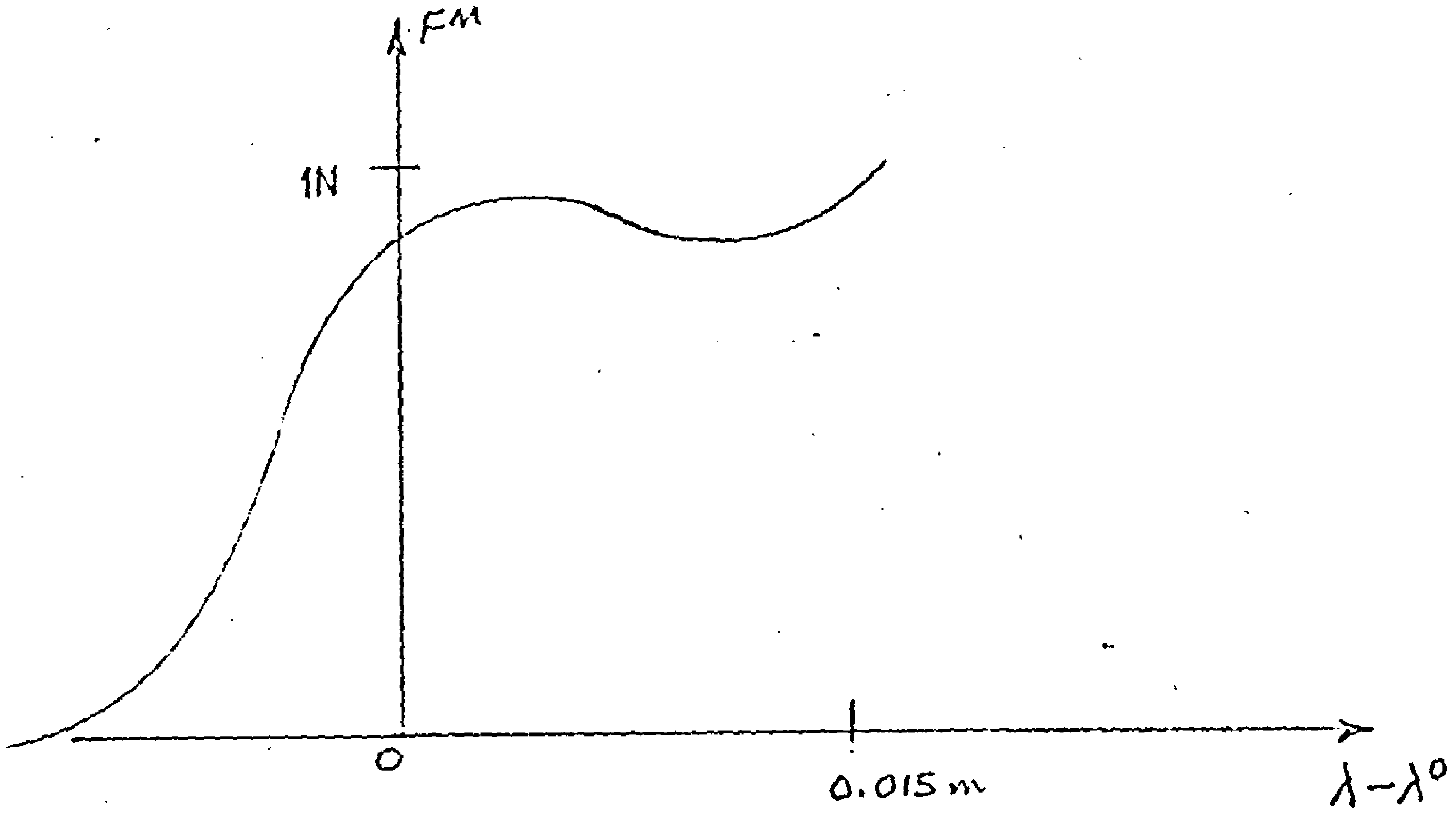


Fig. 3.3.3.1

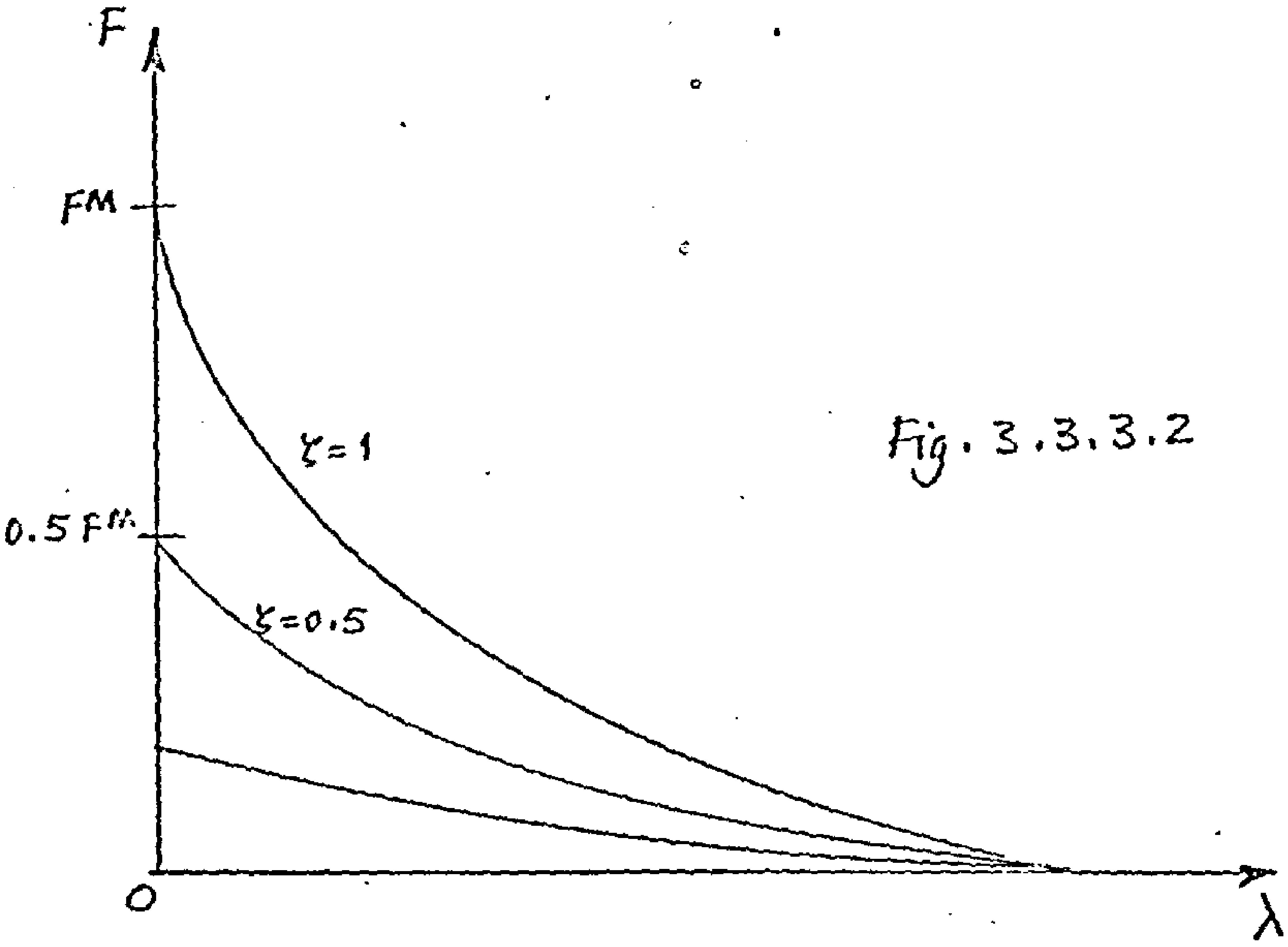


Fig. 3.3.3.2

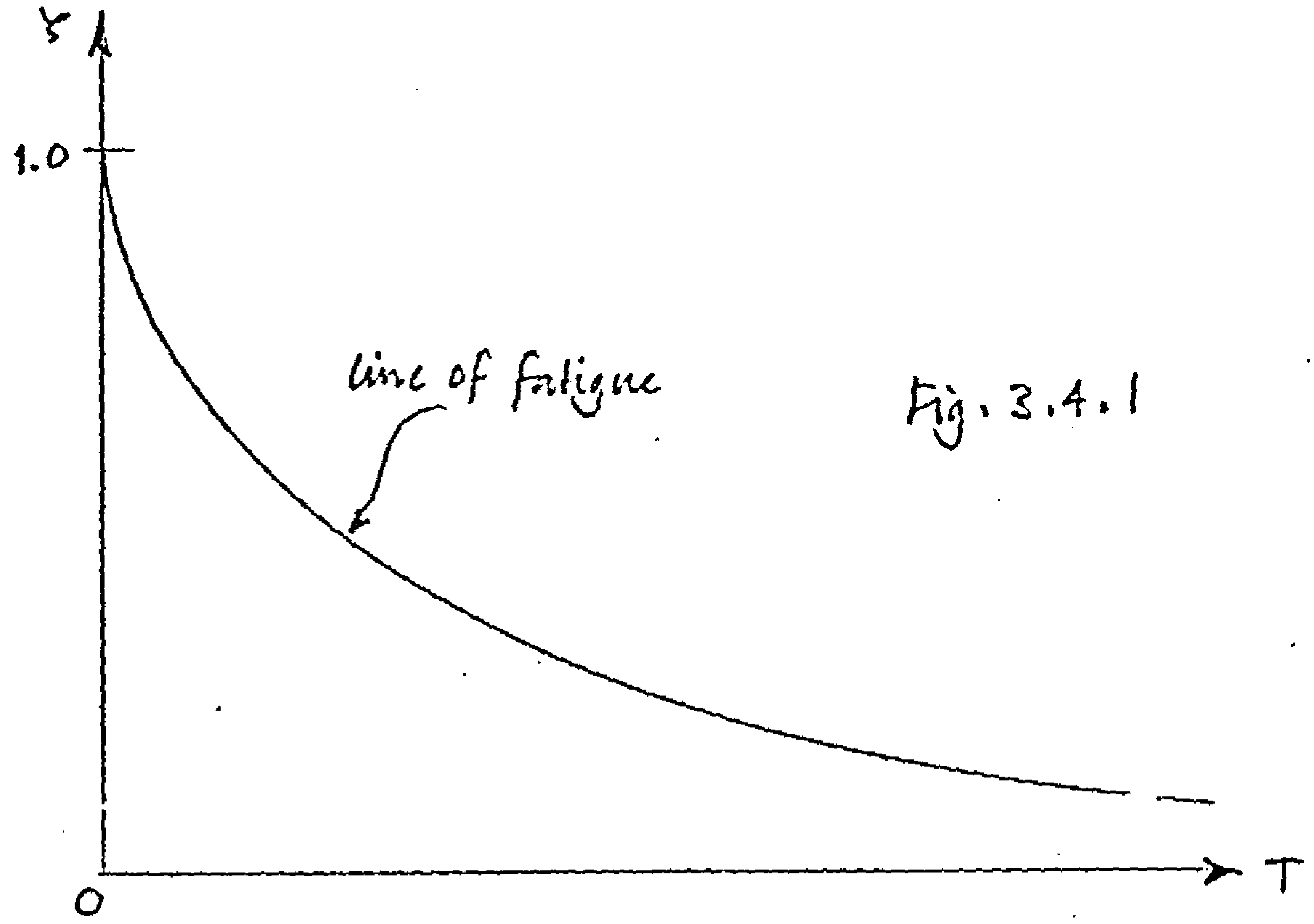


Fig. 3.4.1

we keep the symbol μ to represent the (linearised) viscosity at maximum stimulation, then we can take the general value of the linear viscous element in our model to be $\zeta\mu$.

This still leaves the question of elasticity at different levels of stimulation. Vickers (1968) argues as follows. Suppose that the muscle group has a cross-sectional area A_0 , and that at intermediate levels of stimulation only a certain proportion, A , of the area is active; that is, $A = \zeta A_0$. Now if the elastic component has an unstretched length l_0 , and Young's modulus E , and if it is stretched by an amount δl , then the stiffnes of the element is $k = F/\delta l = EA/l_0 = \zeta(EA_0/l_0) = \zeta\kappa$ where κ is the stiffness when $\zeta = 1$ as before. At this point, Vickers gives Wilkie's curve of stiffness versus tension (Fig. 3.3.2.12), which is very nearly a linearly rising function, and claims that this proves his theory. But Wilkie's curve is not $k(\zeta)$ but in fact $\kappa(F)$, which is not the same thing. Also, Vickers' argument is circular in that he assumes firstly that E is constant for all values of F , and secondly that only the active area, A , of the muscle has elasticity. Thus we have no way of knowing whether Vickers' theory of proportional stiffness is right or not. Accordingly, κ will be taken here as being independent of ζ (which may or may not be true).

Other papers are by (1) McRuer, Magdaleno and Moore (1968), who deduce curves of ζF^M versus $\lambda - \lambda^0$ at different values of ζ , and produce a model of an antagonistic pair of muscles operating around a middle value of tension, and (2) Young and Stark (1965) who describe a digital simulation of an arm model, using Wilkie's data. They also consider the case of a lengthening muscle (we have always been considering a shortening muscle) and take its viscosity, rather arbitrarily, to be six times as great as that of a shortening muscle. However, as a muscle can only be lengthened if it is pulled against its wish, it is doubtful if such a case arises in playing the piano, and so this information will be disregarded - at least for the present.

3.4 FATIGUE

A muscle cannot of course deliver large quantities of force indefinitely. If it is hard worked the chemical impurities which appear in it due to force production cannot be removed fast enough by the blood stream, and so the muscle is not able to keep up its force output.

A rather confused situation exists in the literature as regards the study of fatigue. Merton, in a review (1956), rejects previous work which suggested that fatigue is due to temporary failure of the nervous system and shows that if the flow of blood to a tired muscle is impeded, the muscle will remain in a state of fatigue. (This is in agreement with the idea of chemical impurities). Basmajian, in his review (1967), lists the following types of fatigue : emotional fatigue, central nervous system fatigue, "general" fatigue and peripheral neuromuscular fatigue of special kinds. He goes on to show that very often the chief cause of fatigue is not that the muscles are tired, but that the fibrous tissues (Sec.3.1) which restrain the joints involved have become strained, and that they order the muscles to switch off to avoid damage.

As no suitable data seems to exist for the analysis of fatigue, its treatment in this thesis must be rather hypothetical. The following standpoint will be taken :-

Firstly, any movement which involves stretching a joint against the tissues that limit its range of turning is liable to produce fatigue at that joint.

Secondly, when all the joints involved lie within their normal comfortable range, fatigue depends entirely on muscle power output. From common experience we know that a muscle can exert its maximum force for only a very brief time. We know also that if a muscle is developing only a small fraction of its maximum force, then it can carry on almost indefinitely. Therefore, a graph of the fraction of maximum force developed,

ζ, versus the period of time, T, during which it is sustained would look something like Fig.3.4.1. The more athletic the person is, the more the line of fatigue moves to the right.

In reality, the situation is more complex, because, for example, a muscle which is exerted at 80% of its maximum until it is nearly fatigued can drop to the 20% level and carry on with impunity for a considerable time more. In addition, there is the question of recovery time. Schultz states that if a muscle working near its maximum tension can be relaxed for only a fraction of a second, then much of its fatigue vanishes. This seems quite sensible and is in accordance with the bloodstream theory.

3.5 ENERGY EXPENDITURE

One must be careful in determining the work rate of a muscle. The natural tendency is to evaluate the total kinetic and potential energy given to a load by a muscle group and assume that this is the energy expended by the muscles involved. But this is to ignore the fact that it is possible for a muscle to become tired through doing no "work" whatsoever. For example, if both the raising and lowering muscles of the elbow are fully tensed so that the forearm is stationary, then no useful work at all is performed. However, the muscles are working at a high rate, partly to maintain the weight of the forearm, but mostly to simply antagonize each other. The energy transfer in this case is almost entirely a matter of chemical energy conversion in the muscles.

3.6 STANDARD VALUES OF ARM PARAMETERS

This section gives numerical values to the parameters of arm mechanics which will be used in Chap.4. These values are by no means accurate and are intended as little more than order-of-magnitude values. Actually, there is not much point in working out the precise mean values of the parameters of the population as a whole, because naturally any piano method, if it is to be of value, must be as little sensitive as possible to variations in parameters. It is the aim of the calculations in this thesis to illustrate a point made or to highlight a popular fallacy, and for this only typical values are needed.

All the data has, of course, to form a compatible set, and some judicious adjustment of the values taken from the literature has been carried out to achieve this.

The data given in this section is summarized in Appendix 2.

3.6.1 Lengths

The following lengths are typical of a person of average build, (they are actually my own personal measurements). Each link is measured between the apparent centres of rotation.

Upper arm : 0.35 metres
Forearm (from elbow to wrist) : 0.27 metres
Hand (from wrist to tip of fingers,
with fingers in average position) : approx. 0.15 metres
Forearm from elbow to centre of hand,
when hand is clenched : 0.35 metres

3.6.2 Maximum Strengths

These maximum strengths of individual muscle groups are again personal measurements. The values are expressed as moments and are measured over the middle range of turning of the joints, the arm being held out in front of the body.

Shoulder (up and down) : 100 Nm
Elbow (up and down) : 65 Nm
Wrist (up and down) : 10 Nm
Typical finger (down) : approx. 1 or 2 Nm

3.6.3 Masses, etc.

Williams & Lissner (1962) give the following typical masses:-

Upper arm only : 1.6 kg
Forearm only : 0.95 kg
Hand (including fingers) : 0.4 kg

They also give the centre of mass of the upper arm as 44% of the way from the shoulder (this gives a distance of 0.15m, using the length of Sec.3.6.1). The centre of mass of the forearm only is given as 43% of the way from the elbow (giving 0.12m). From this we can calculate the centre of mass of the forearm and hand (in average position) to be 0.19m from the elbow.

Bouisset and Pertuzon (1967) give the moment of inertia of the forearm and hand about the elbow with the wrist rigid and the hand clenched as 0.0599 $kg.m^2$ (a delightful result, considering only eleven subjects were used).

Taking the radius of gyration of the hand about the wrist to be about 0.08 m, the moment of inertia of the hand is about 0.0025 $kg.m^2$.

3.6.4 Compatible SEMs

If we take the lever arm of the SEM governing the elbow as 0.04 (Sec.3.3.2), then the maximum strength of the SEM must be 65/0.04 N to be compatible with the moment strength quoted before. For numerical convenience, the moment strength will be taken as 64 Nm and the force strength as 1600 N.

By direct measurement, the thickness of the wrist is about 0.04 m, giving an SEM acting on the wrist of 500 N at a lever arm of 0.02 m.

3.6.5 Muscle Properties.

Wilkie gives five curves of viscosity, similar to Fig.3.3.2.3, representing five subjects. If they are linearised (by connecting the end points) and scaled to represent SEM components, the values of μ lie between 1370 Ns/m and 2610 Ns/m. The standard value is here taken as a constant 1950 Ns/m. As there is such individual variation, there seems at this stage little point in taking μ as nonlinear. Wilkie also gives five values of κ measured under the condition that $F = 2F^M/3$. These values lie between 21000 N/m and 153000 N/m. (This is a great variation). The standard value is here taken as a constant 80000 N/m.

Unlike the other dimensions, about which there can be little doubt, these parameters of the muscles are only put forward on a temporary basis; in Chap.4, they will be examined to test their accuracy.

3.6.6. Reciprocal SEMs

As there seems to be little difference between muscular action upwards or downwards, the SEMs acting on either side of a joint will be considered identical. Their lever arms will also be considered identical, although the muscles which lower the forearm, for example, do not stick out from the back of the elbow by as much as 0.04 m. However, the criterion of an arm model is that it should predict behaviour, rather than look realistic.

4

SIMULATION OF BASIC ARM MOVEMENTS

4.0 INTRODUCTION

This chapter is concerned with simulating skilled movements of the arm. The whole chapter is developed with little direct reference to piano playing, and is thus of general biomechanical interest.

Movements can be split into two classes: fast movements and slow movements. It is well known that the reaction time of test pilots and rally drivers is in the range 0.1 to 0.2 sec. By "reaction time" is meant the time taken to detect a change in the environment and to take appropriate action (attempting to do this as fast as possible, of course). Thus, movements taking longer than about 0.2 sec. can be modified en route, and these may be classed as slow movements. Conversely, it seems reasonable to assume that movements taking less than about 0.2 sec. are over before it is possible to modify them, and these may be classed as fast movements. Clearly, such movements must be planned in advance. This is not to suggest that fast movements are totally uncontrolled; it is possible that there are automatic feedback systems within the nervous system which exert their influence on rapid movements. The point being made is that it is not possible to consciously alter any aspect of nervous control during a rapid movement.

Slow movements will not be considered further in this thesis, for two reasons. Firstly, the time taken to depress a piano key, according to Ching, is always less than 0.1 sec. Therefore practically all movements of interest in piano playing are fast movements, under our definition. Secondly, the control of slow movements is mainly dependent on decision-making processes in the brain and on the efficient operation of the nervous system, and these topics, as stated in Chap. 1, lie outside the scope of this thesis.

The fact that a slow movement may be repeated is of no great significance, but with fast movements there is quite a difference between single, "one-shot" movements and repeated, oscillatory movements. This is because, due to a certain amount of mechanical sluggishness in the arm, the after-effects of a movement last about 0.2 sec. (as will be seen) and hence, in a fast oscillation, one movement interferes with the next.

The simulations in this chapter will begin by considering fast oscillations, because, as far as simulation techniques are concerned, a one-shot movement is just a special case of an oscillation.

It was shown in the last chapter that the arm can be considered as a movable structure equipped with force actuators. Hence, in setting up a mathematical model of the arm, two types of model arise: models of the structural parts of the arm, and models of the muscles.

As in the last chapter, attention will be centred on the elbow and general deductions as to the behaviour of this joint will be applied to the other joints of the arm.

4.1 MODELLING THE STRUCTURAL PARTS OF THE ARM

The arm, as we can see, consists of a set of hinged links with a covering of flesh, so naturally in setting up a mathematical model one would choose as a basis a set of equations which describe an ideal set of hinged links. If we assume that these equations represent an actual arm, then we are making the following approximations :-

1. Each link is considered rigid. In fact, the arm is made up partly of flesh, which has a tendency to shift around, particularly during rapid movements. However, this movement is unlikely to cause a substantial change in the value of the moment of inertia.

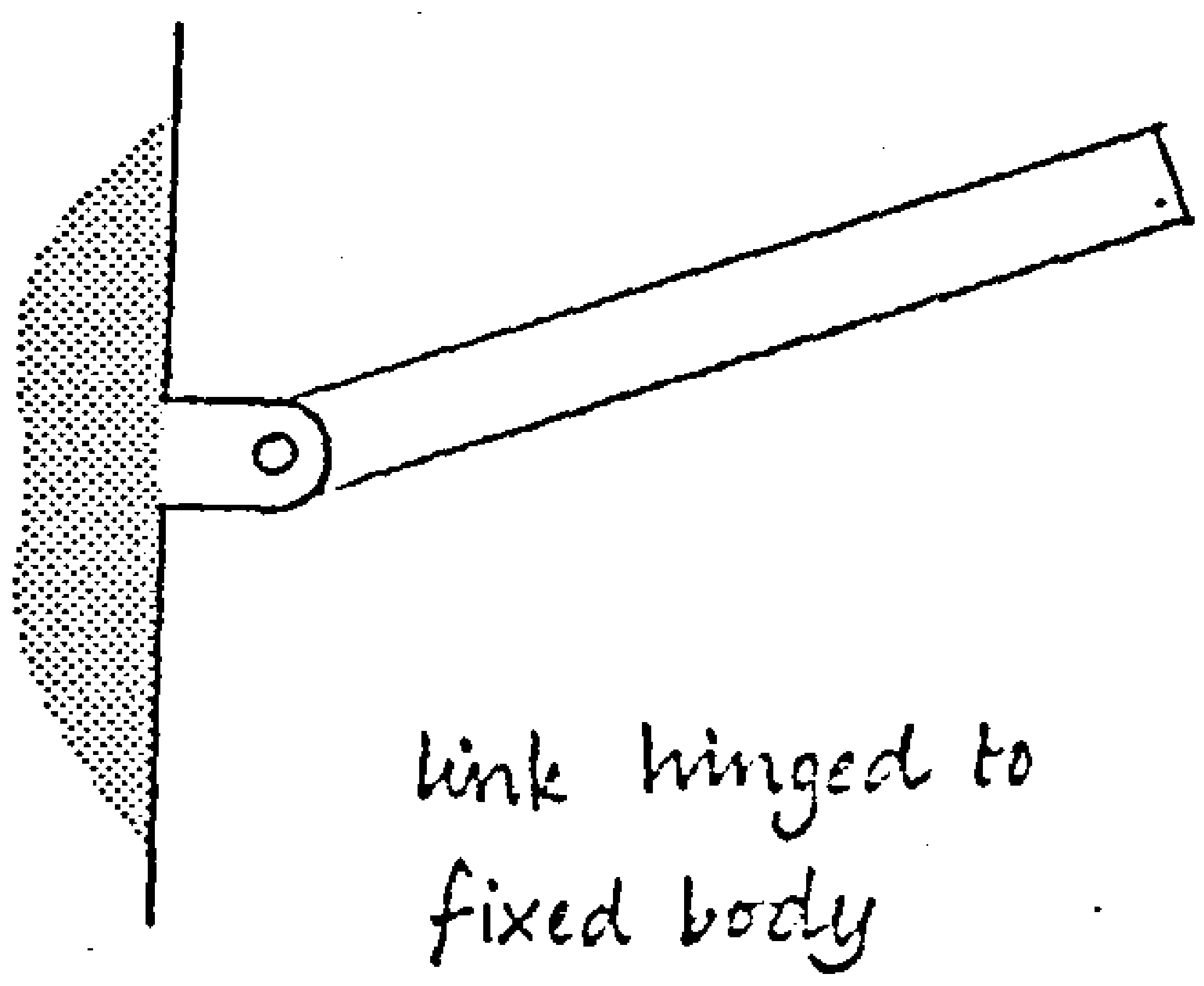
2. Each joint is considered frictionless. This is quite near the truth, as was discussed in Chap.3.

It must be made clear that the models represent the whole arm rather than the skeleton. For example, the value given for the moment of inertia of the forearm includes the inertia of the flesh (and hence the muscles) as well as the bones.

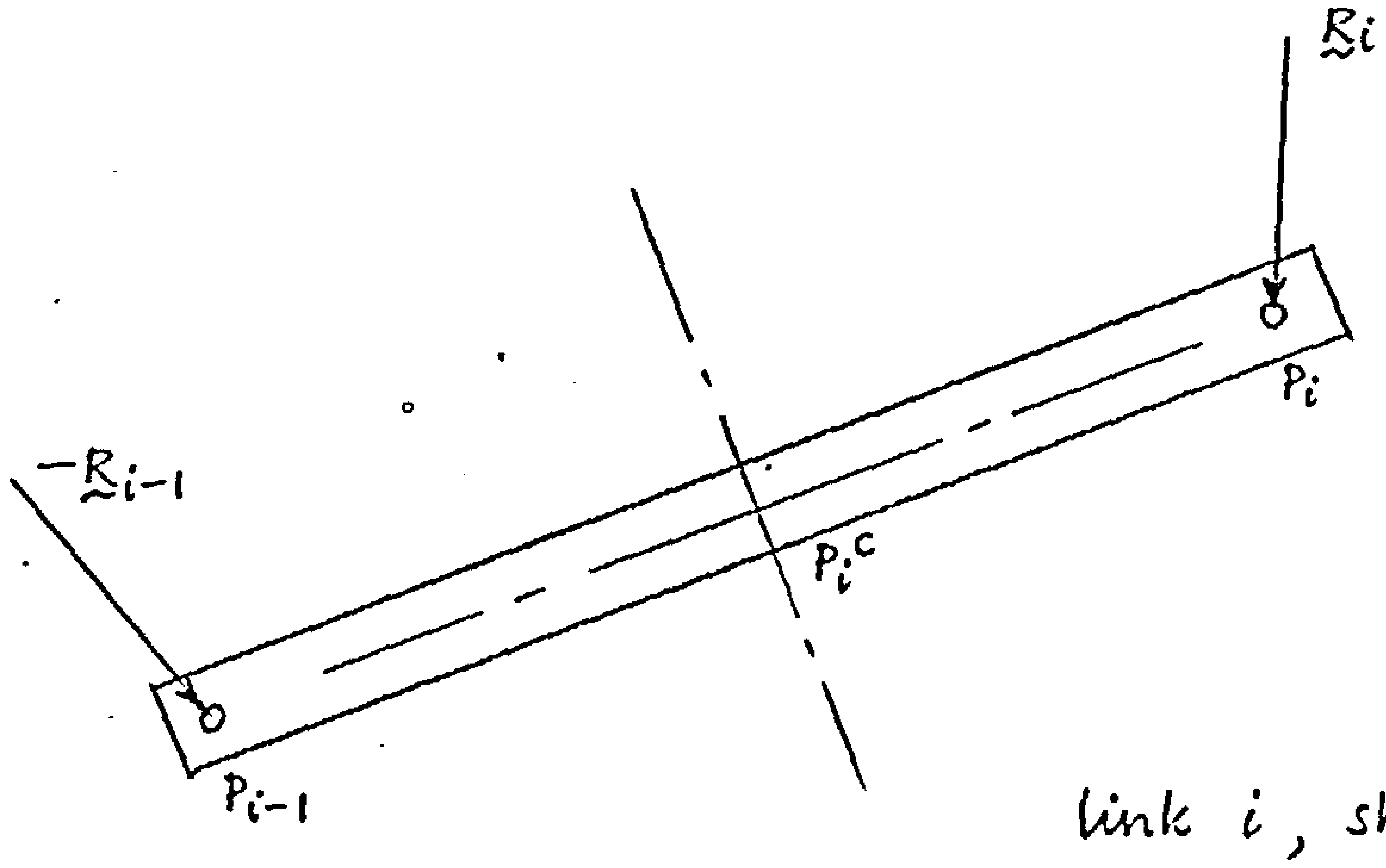
In the diagrams in this chapter, each link is represented by a long rectangular area and each joint by a small circle. (The joints do not necessarily lie at the ends of the links). Points which are fixed with respect to the inertial frame of reference are indicated by shading. Forces are shown by straight arrows and moments by curved arrows (Fig.4.1.1).

The following symbols are used (see also Appendix 6) :-

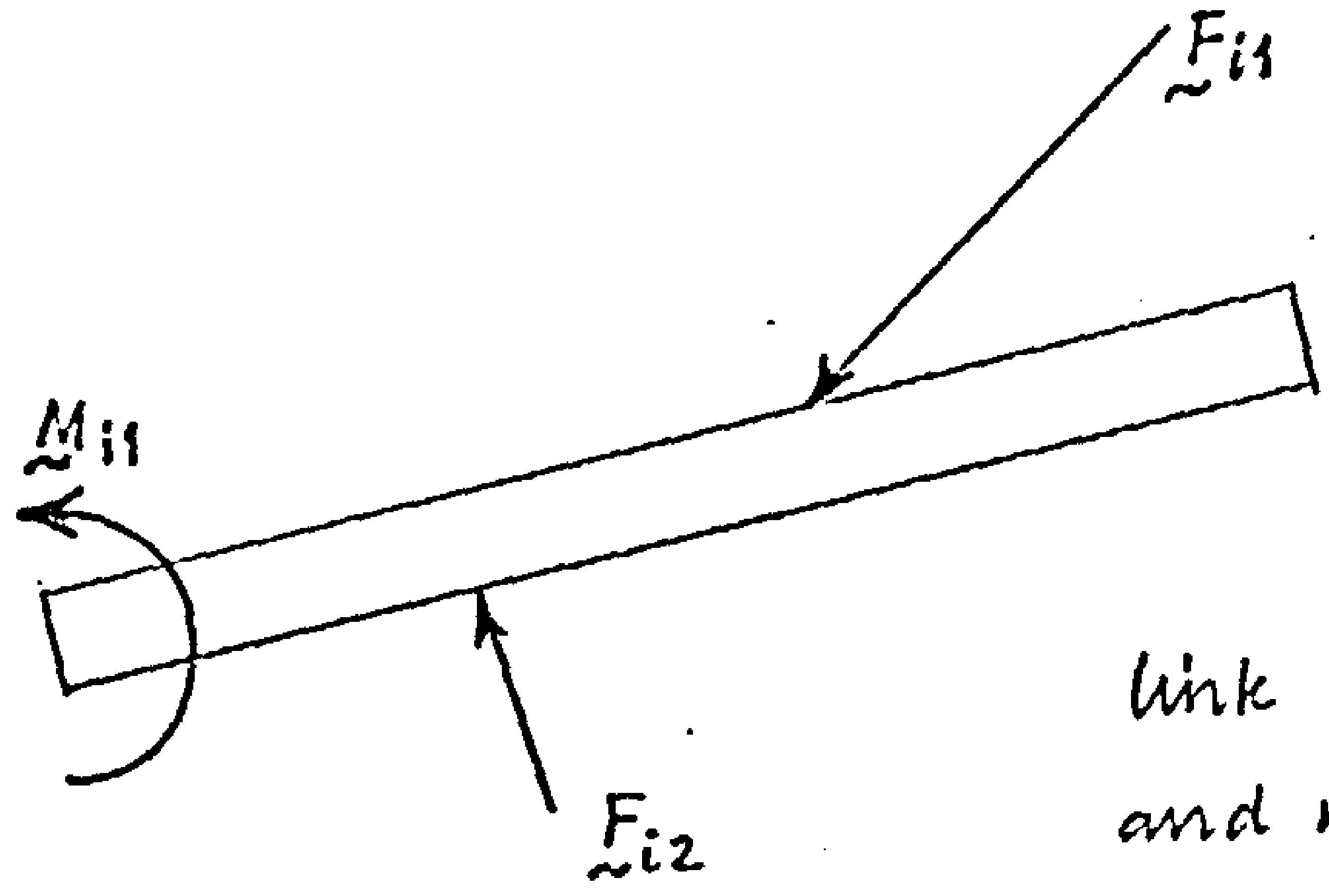
Each link is assigned a number, generally designated i . Points fixed with respect to the inertial frame of reference are all considered to lie on link 0. The points on link i at which the joints lie are designated P_{i-1} and P_i, so that P_i is the point



link hinged to fixed body



link i, showing points and reactions



link i, showing forces and moments acting

Fig. 4:1.1

of connection of link i and link $i+1$. Thus link 1 is anchored to the origin at point P_0, which is fixed inertially. The point of the centre of mass of link i is designated P_i^c . The link i is acted on, in general, by a system of forces (other than reactions at the joints) $\underset{\sim}{F}_{ik}$ and pure moments $\underset{\sim}{M}_{il}$. The points at which the forces $\underset{\sim}{F}_{ik}$ act are designated P_{ik} and the interior angle that the force $\underset{\sim}{F}_{ik}$ makes with the axis of link i is designated ψ_{ik} . The reaction at P_i acting on link i is designated $\underset{\sim}{R}_i$. The following set of position vectors is used :-

$$\underset{\sim}{l}_i = \overrightarrow{P_{i-1}P_i}$$

$$\underset{\sim}{r}_i = \overrightarrow{P_0\,P_i^c}$$

$$\underset{\sim}{s}_i = \begin{cases} \overrightarrow{P_0\,P_1} & \text{when } i = 1 \\ \overrightarrow{P_i^c P_i} & \text{when } i \neq 1 \end{cases}$$

$$\underset{\sim}{p}_{ik} = \begin{cases} \overrightarrow{P_0\,P_{ik}} & \text{when } i = 0 \text{ or } 1 \\ \overrightarrow{P_i^c P_{ik}} & \text{when } i \neq 0 \text{ or } 1 \end{cases}$$

In addition the parameters m_i and I_i , representing the mass and moment of inertia of link i are used. When $i = 1$, I_1 is taken about P_0 ; when $i \neq 1$, I_i is taken about P_i^c .

In general, $\underset{\sim}{l}_i$, $\underset{\sim}{r}_i$, $\underset{\sim}{s}_i$, $\underset{\sim}{p}_{ik}$, $\underset{\sim}{F}_{ik}$, $\underset{\sim}{M}_{il}$ and $\underset{\sim}{R}_i$ are functions of time, whereas l_i , m_i , I_i and s_i are normally constant.

The equations of displacement and motion are :-

$$\underset{\sim}{r}_i = \sum_{\alpha=1}^{i} \underset{\sim}{l}_\alpha - \underset{\sim}{s}_i \qquad i \neq 1 \tag{4.1.1}$$

$$\sum_k \underset{\sim}{F}_{ik} + \underset{\sim}{R}_i - \underset{\sim}{R}_{i-1} = m_i \ddot{\underset{\sim}{r}}_i \tag{4.1.2}$$

$$\sum_l \underset{\sim}{M}_{il} + \sum_k \underset{\sim}{p}_{ik} \times \underset{\sim}{F}_{ik} + \underset{\sim}{s}_i \times \underset{\sim}{R}_i - (\underset{\sim}{s}_i - \underset{\sim}{l}_i) \times \underset{\sim}{R}_{i-1} = I_i \ddot{\theta}_i \underset{\sim}{u} \tag{4.1.3}$$

where $\underset{\sim}{u}$ is an appropriate unit vector, and $\ddot{\theta}_i$ is the angular acceleration of link i in the plane defined by $\underset{\sim}{u}$. These are the general equations of a system of links, forces and moments. In fact, in this thesis, the models studied are not very elaborate and so the notation used is simplified; suffixes are employed only where necessary. Furthermore, the treatment of these equations is restricted to two dimensions; in this case, all joints become planar hinges, $\underset{\sim}{u}$ lies normal to the plane considered, and $\underset{\sim}{l_i}$ can be taken as the vector (x_i , y_i) in Cartesian co-ordinates or (l_i , θ_i) in polar co-ordinates, where x_i and y_i are the usual space variables and θ_i is the angle made by link i with the horizontal, measured counter-clockwise. Note, however, that these angles θ_i are defined differently from the θ of Wilkie's experiment (Sec.3.3).

4.2 MODELLING THE MUSCLES

The basic model of a muscle (or single equivalent muscle) was discussed in Chap.3. When more than one muscle appears in an arm model, the muscles are each assigned a number, generally designated j, and this number is used as a suffix for the muscle parameters.

As a muscle is attached to the bone by connective tissue, the width of which is in general small compared with the length of the link, each muscle will be considered to exert a point force on its link.

Muscles will always be considered to lie in a straight line between their ends. This may not be altogether true at low levels of stimulation, as relaxed muscles are quite flabby, but at moderate stimulation, the assumption is obviously true in most cases. If the muscles lie in straight lines, then their lengths can be calculated by the usual sine and cosine rules.

4.3 SIMULATION OF ELBOW ROTATION

The rest of this chapter is concerned with the simulation of basic arm movements, using the mathematical models just defined. In trivial cases the equations are simply worked out analytically; those that are worked out by computer are labelled with a program number. The computer techniques used are discussed in Appendix 1. The standard values of Appendix 2 are always used, unless it is stated otherwise.

To begin with suppose we consider the simple up-and-down motion of the forearm, rotation taking place at the elbow, with the upper arm fixed and the wrist and hand rigid (Fig.4.3.1). The action of the muscles may be represented by a pure moment $M(t)$. The model is unaffected by the angle of the upper arm.

The equation of motion for the system (neglecting gravity) is:-

$$M(t) = I\ddot{\theta}(t) \tag{4.3.1}$$

Suppose we consider $M(t)$ to be just switched alternately positive and negative. To define $M(t)$ we must first define the intervals

$$0 < t < T \quad \text{and} \quad (4n-1)T < t < (4n+1)T$$

where T is constant and $n = 1,2,3,\ldots.$ as "positive intervals" and the intervals

$$(4n-3)T < t < (4n-1)T$$

as "negative intervals". Then if we take (Fig.4.3.2)

$$M(t) = \begin{cases} +M_0 \text{ over positive intervals} \\ -M_0 \text{ over negative intervals} \end{cases} \tag{4.3.2}$$

where M_0 is a constant, and if $\theta(0) = \dot{\theta}(0) = 0$, then

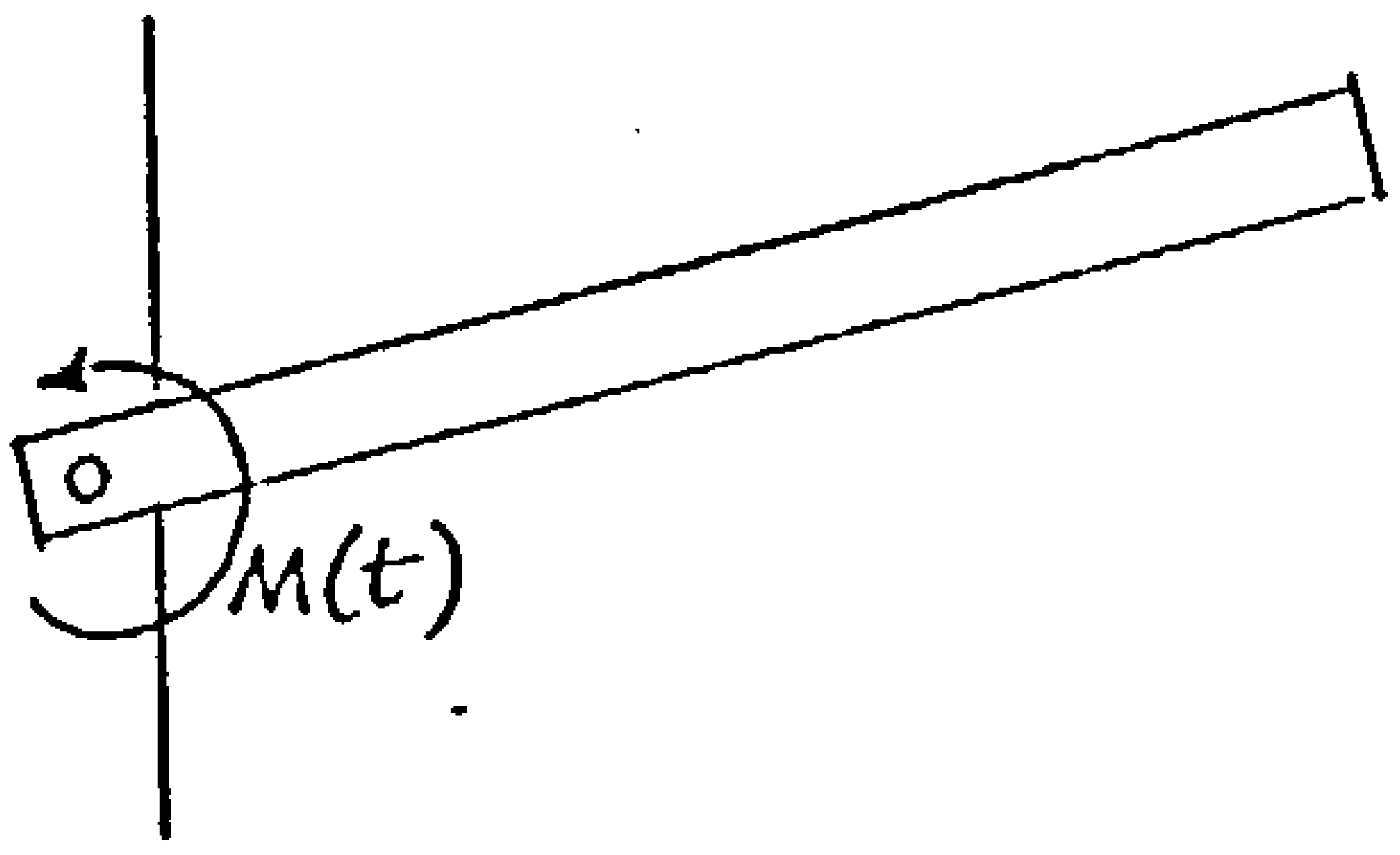


Fig. 4.3.1

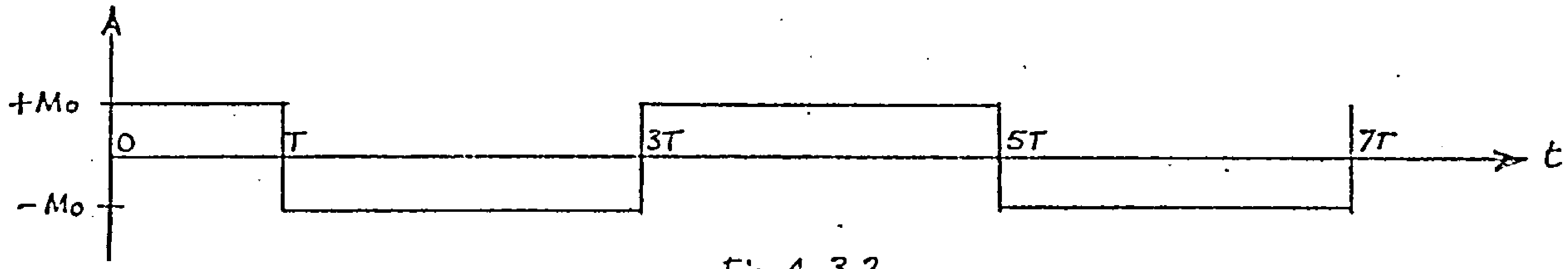


Fig. 4.3.2

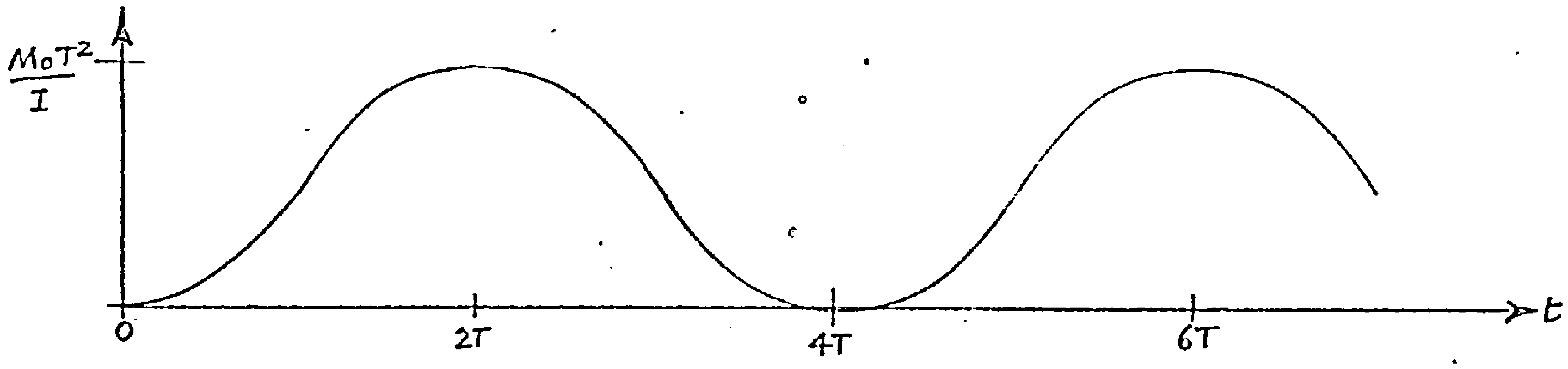


Fig. 4.3.3

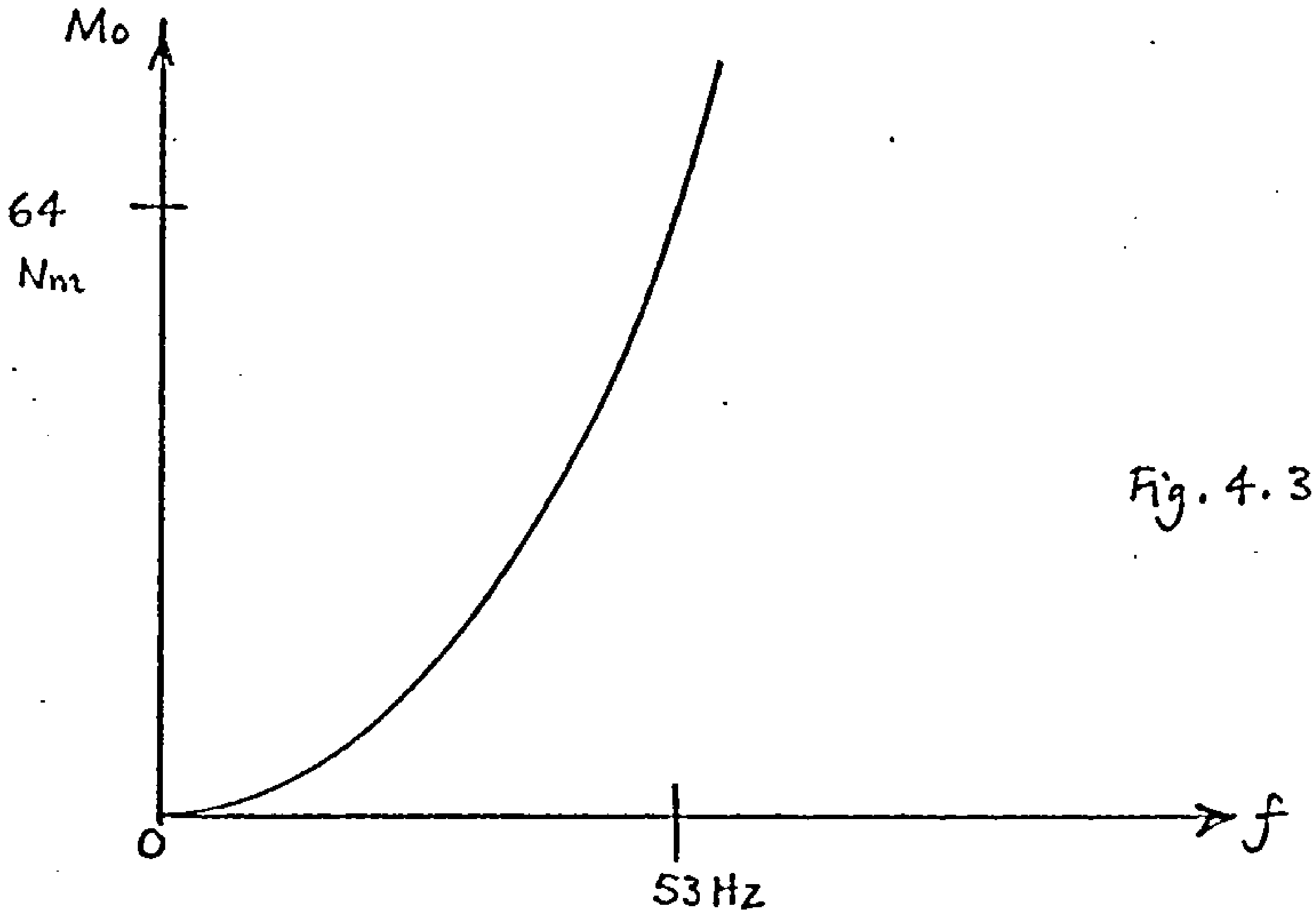


Fig. 4.3.4

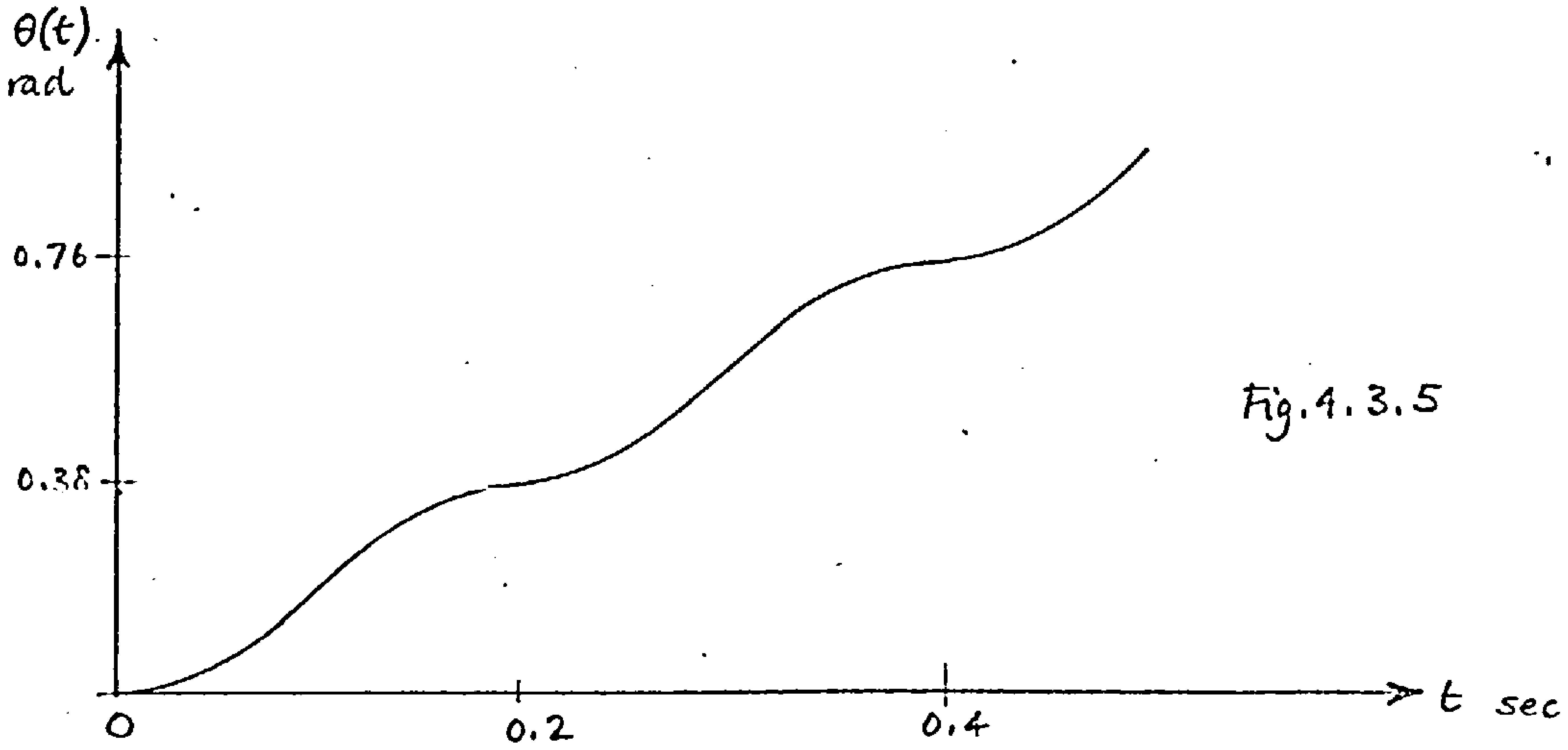


Fig. 4.3.5

$$\theta(t) = \begin{cases} (M_0/2I)\,t^2, & 0<t<T \\ (M_0/2I)(t-4nT)^2, & \text{over the remaining positive intervals} \\ (M_0/2I)\{2T^2-(t-\overline{4n-2}\,T)^2\}, & \text{over negative intervals} \end{cases} \tag{4.3.3}$$

which gives the required oscillation (Fig.4.3.3)

Suppose we want the tip of the link to describe an oscillation of 0.01 metres, peak to peak. (This is the displacement of a piano key). Then the moment required is

$$M_0 = 0.01\, I/T^2 l \tag{4.3.4}$$

where the usual small arc approximation has been used.

The frequency, f, of the oscillation is given by:-

$$f = 1/4T \tag{4.3.5}$$

Hence

$$M_0 = 0.16\, I f^2/l = 0.023 f^2 \tag{4.3.6}$$

Thus we can see how the inertial properties of the arm grow increasingly important as speed increases (Fig.4.3.4). If we take M_0 to be the standard maximum strength, $M^M = 64$ Nm, the maximum frequency attainable (in theory) is 53 Hz. This value should not be taken too seriously, as the model is very crude.

It is interesting to see how much effect gravity has on this motion. Adding a gravity term to the previous equation of motion, we have (using the usual small-angle approximation)

$$M(t) - mgr = I\ddot{\theta}(t) \tag{4.3.7}$$

Now to preserve the same regular-shaped output as before (Fig.4.3.3), the input must be modified. For maximum speed we must use the maximum strength M^M for upward movements, but to preserve a balance we must decrease the downward moment to $M^M - 2mgr$. Thus the strength available has effectively been decreased to $M^M - mgr$, which is a proportional decrease of $mgr/M^M = 2.5\%$

We can say, then, that the force of gravity does not appreciably affect high-speed oscillation.

Of course, altering the amplitude is not the only way of compensating the input. Equally well, the frequency could be altered, and this brings us to an important point. In order to get a satisfactory output, consisting of parabolic segments (Fig.4.3.3), it was necessary to start the input carefully, with a half step. Suppose we had not done this, and for the sake of argument had taken the input function as

$$M(t) = \begin{cases} +M_0\ , & (4n-4)T < t < (4n-2)T \\ -M_0\ , & (4n-2)T < t < 4nT \end{cases} \qquad (4.3.8)$$

with $T = 1/40$ sec (to give $f \doteq 10$) and $M_0 = 2.3$ Nm, ignoring gravity. The output which would have resulted is shown in Fig.4.3.5 (Program 4-1). Everything is wrong with this output - the oscillation has become quite unstable. And yet, this is the result of altering just one step in the input. The crux of the matter is that if any parabolic segment hands over to the next one at any instant other than the theoretically exact one, then all succeeding segments will have been sent off course. There is an important lesson to be learned from this, which is that a very fast oscillation needs a great deal of strength, but if all the strength of the muscle group involved is used, then the resulting motion is almost bound to be completely out of control. This is because the slightest inaccuracy in the input must be corrected by adjustment of the amplitude or duration of at least one of the next few input steps. It really does not seem likely that a muscle group can do this beyond about 6 Hz or so, when in reality the input signal to each muscle consists of a series of frequency-modulated spikes. It is probably as much as the nervous system can do to switch a muscle on and off, without having to produce fancy-shaped functions. In view of this, it seems reasonable to suggest that the only possible way in which a stable oscillation at maximum speed can take place is that some muscles switch on and off at their maximum magnitude, regardless of limb position, and that the remaining muscles at the joint are concerned solely with preserving stability, that is they are in a continuously switched-on condition with their amplitudes varying as appropriate to steer the limb to the right average position. This point will be taken up in the next section.

4.4 THE EFFECT OF MUSCLE ACTION ON THE ELBOW

Let us now look at a more sophisticated model - that of a single link acted on by two SEMs (Fig.4.4.1). This represents the normal pair of antagonistic muscle groups acting on the elbow. The shoulder and upper arm are held stationary, and the forearm can oscillate up and down. The model can of course also represent two single muscles acting on the elbow, if the parameters are suitably altered.

Fig.4.4.2 shows the notation (as defined in Sec.4.1) used for the various lengths in the model. The equations of motion and geometry for the system are as follows. Gravity is ignored and j takes the values 1,2.

$$\theta_j^*(t) \triangleq \begin{cases} 90^\circ - \theta(t), & j=1 \\ 90^\circ + \theta(t), & j=2 \end{cases} \tag{4.4.1}$$

$$p_1 F_1(t) \sin\psi_1(t) - p_2 F_2(t) \sin\psi_2(t) = I\ddot{\theta}(t) \tag{4.4.2}$$

$$\lambda_j(t) = \{p_0^2 + p_j^2 - 2p_0 p_j \cos\theta_j^*(t)\}^{1/2} \tag{4.4.3}$$

$$\dot{\lambda}_j(t) = (-1)^j p_0 p_j \sin\theta_j^*(t) \, . \, \dot{\theta}(t)/\lambda_j(t) \tag{4.4.4}$$

$$\sin\psi_j(t) = \{p_0/\lambda_j(t)\} \sin\theta_j^*(t) \tag{4.4.5}$$

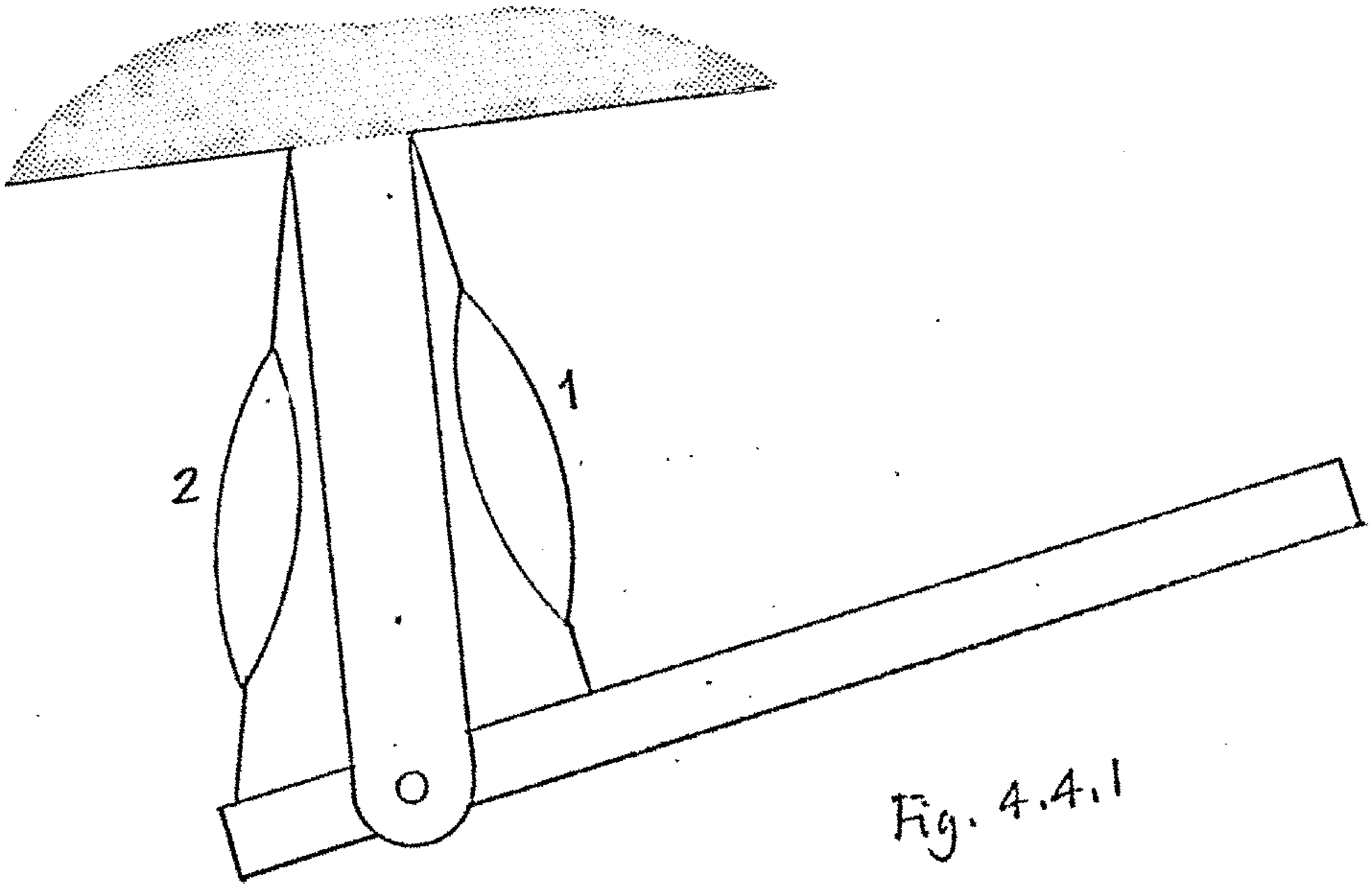


Fig. 4.4.1

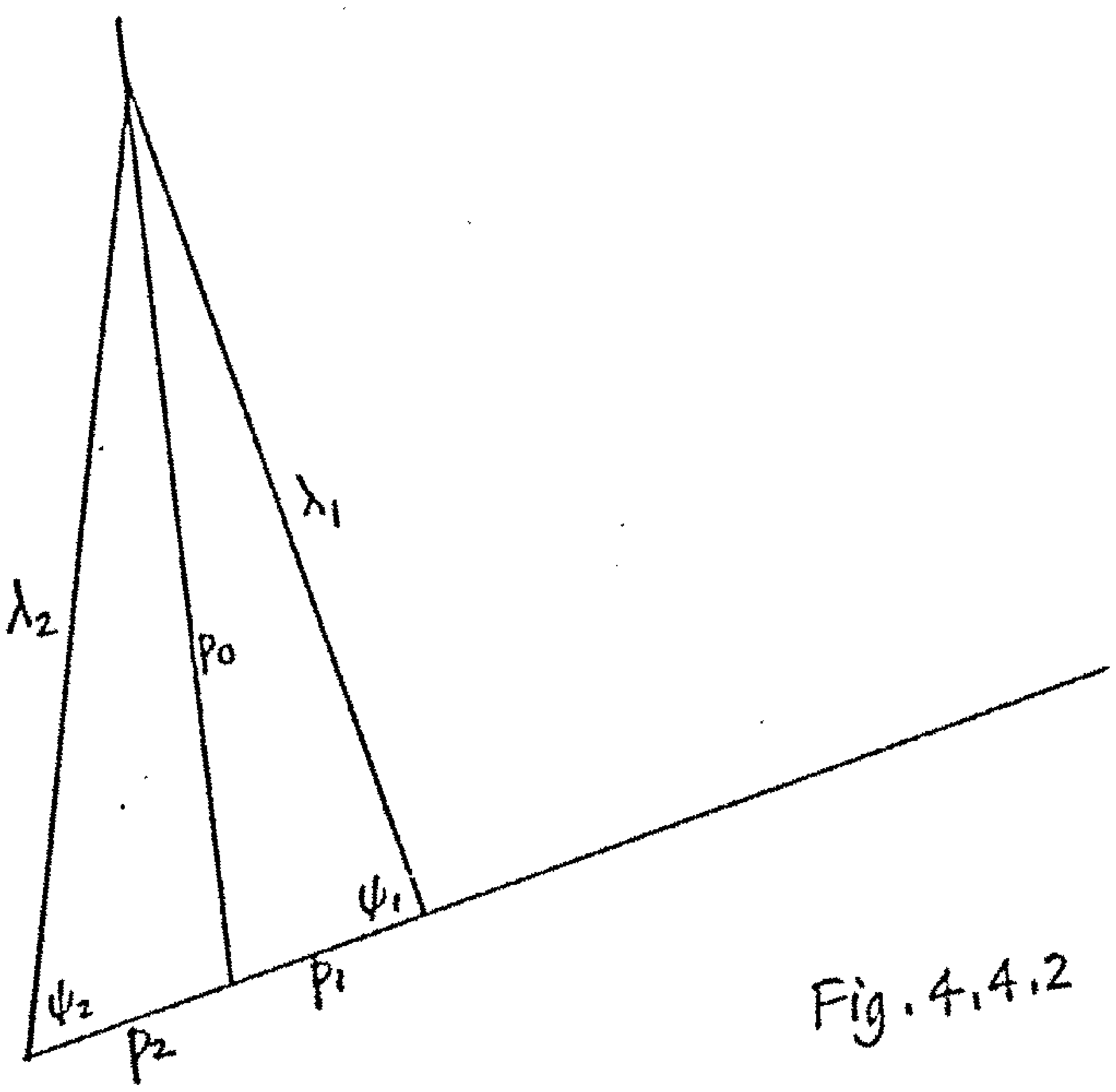


Fig. 4.4.2

We can add to these, provisionally, the equation of muscle properties (derived from equ.3.5). The force-producing element has magnitude ζF^M, the viscous element magnitude $\zeta\mu$, and the spring element κ. The quantities F^M, μ and κ are constant and have been taken as similar for both muscles:-

$$\dot{F}_j(t) = \kappa\dot{\lambda}_j(t) + \{\kappa/\zeta_j(t)\mu\}\{F^M\zeta_j(t) - F_j(t)\} \qquad (4.4.6)$$

The model will now be studied under various conditions.

4.4.1 Static Condition

Firstly, we ought to check the accuracy of the model when the parameters are constant. The best way of doing this is to re-enact Wilkie's third experiment (Fig.3.3.1.4) which plots the rise in tension when the arm is held stationary.

Putting the following conditions on the above equations:

$\zeta_1(t) =$ unit step function, $\zeta_2(t) = \theta(t) = \dot{\lambda}_1(t)$
$= \dot{\lambda}_2(t) \equiv 0$, the torque developed

$$G(t) = p_1 F_1(t) \sin\psi_1 \qquad (4.4.7)$$

may be simulated (Program 4-2). The result of such a simulation is shown, together with Wilkie's curve, rescaled to represent torque, in Fig.4.4.1.1. We can see from this that our gambit of choosing constant κ and μ has apparently failed. On reflection, this is not really surprising, as the simulated curve is simply an exponential rise with a time constant of μ/κ = 0.024 sec., which obviously represents a much faster rise than that in reality. The values of κ and μ that we have been using are the averages of those of the five subjects who were used in Wilkie's experiments. Fortunately, Wilkie labels his data, enabling us to work out the quantity μ/κ for each subject. This gives a set of results lying between 0.01 sec. and 0.12 sec. Considering that the ages

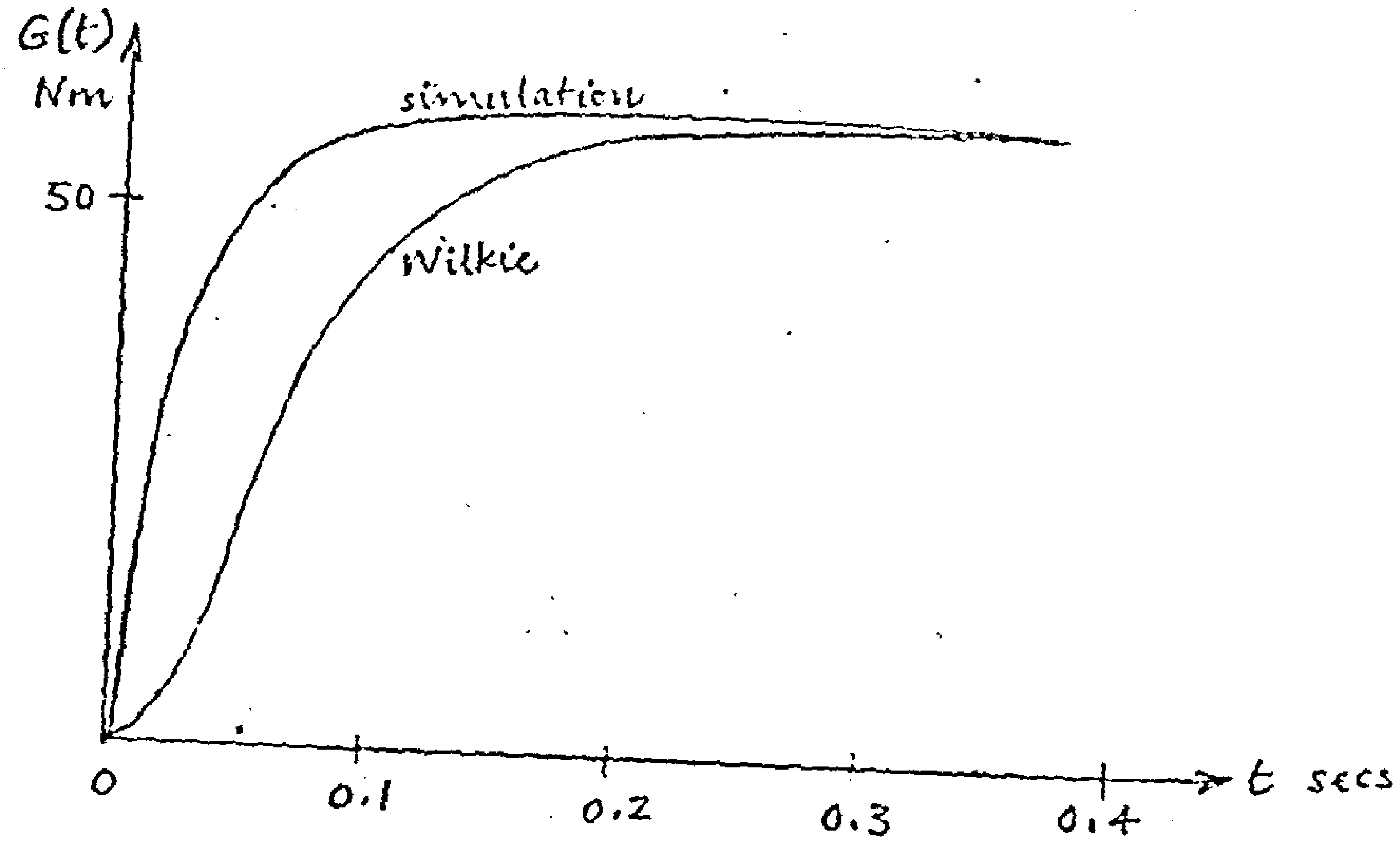


Fig. 4.4.1.1

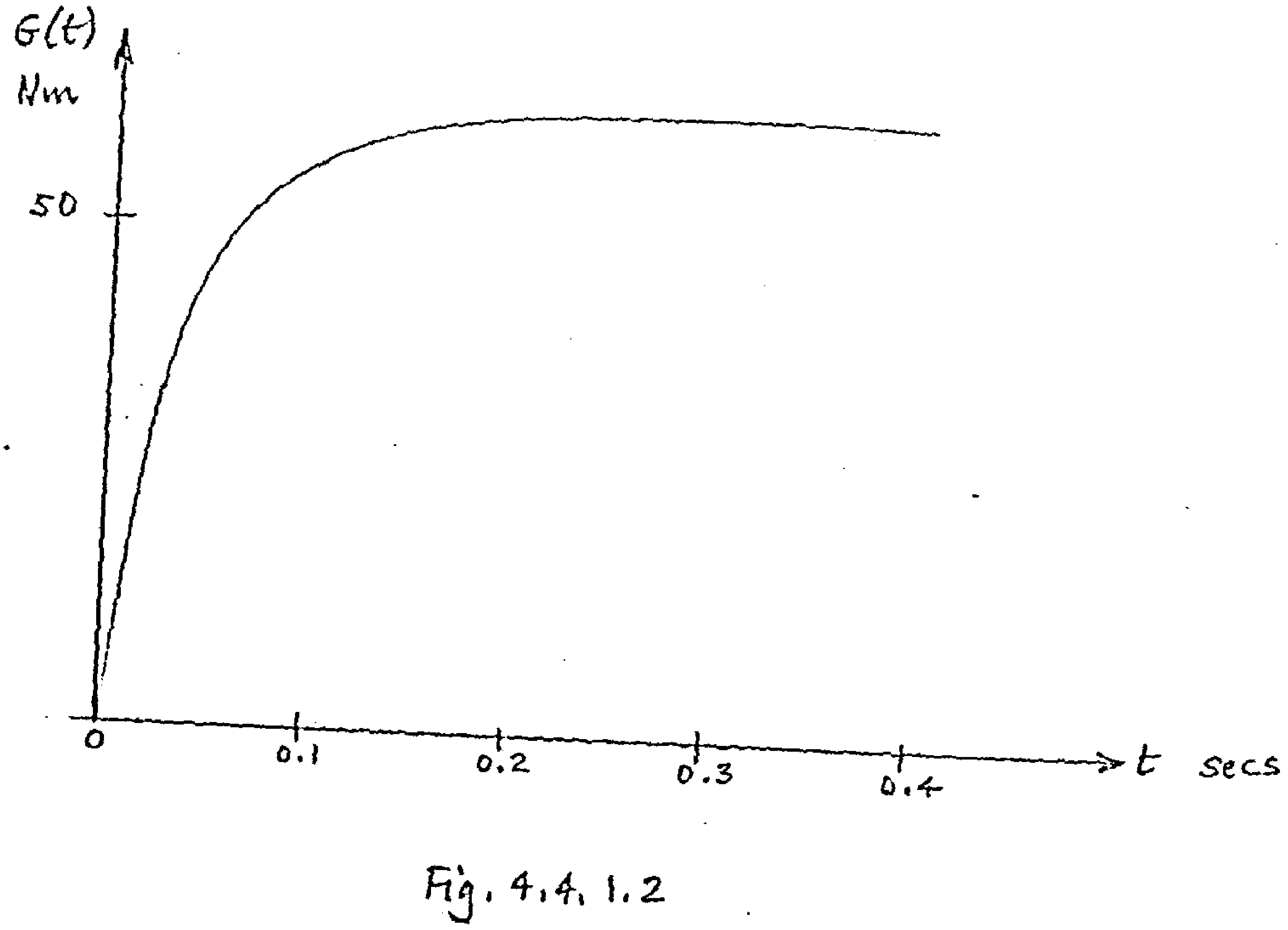


Fig. 4.4.1.2

of the subjects lie only between 20 and 24, these time constants are quite unsatisfactory - it does not seem at all likely that the properties of human arms could vary so much. There are presumably two reasons for the variation in the time constants; firstly the fact that μ and κ have been taken as constant, and secondly, the fact that the values of κ were measured only at $F = 2F^m/3$, which does not necessarily represent an average value in any subject. Actually, both Young and Stark (1965) and Vickers (1968) use constant values and seem to be happy with the result. Fortunately, Wilkie gives a more comprehensive set of results for one subject (himself, as it happens), showing the force-velocity curve, the rise of velocity, the rise of tension, and the whole stiffness curve. It seems prudent to abandon any ideas of taking an average value (between individuals) of any parameter, and instead rely on this one set of results. We know that these results form a compatible set, so if we put them in our model instead of the supposed average values we can expect the results of the simulation to be more sensible. At least we know that one human arm once did behave like that.

Ching, in his 1934 book, briefly discusses the rise time of a muscle group and gives the time taken by a muscle group to make a small contraction to be about 0.05 sec. This agrees roughly with Wilkie's curve.

Replacing the constant value of μ with a variable one is no real problem. As the viscosity curves (Fig.3.3.3.2) were obtained experimentally, one simply has to find an equation which fits each curve. Both Wilkie (1950) and Bigland and Lippold (1954) do this, choosing equations which reflect the energy exchange in the muscles, and their equations can be written as follows:-

$$\{F(t)+\beta_a\}\{\dot{\alpha}(t)+\beta_b\} = \{\zeta(t)F^M+\beta_a\}\beta_b \qquad (4.4.8)$$

where β_a and β_b are constants. We are now considering the force-producing element and the viscous element to be one composite nonlinear element with the above characteristic equation, although it would be more meaningful to keep two separate components and work out the function $\mu(F)$. Values of the two constants compatible with Wilkie's results are: β_a = 3.4 N and β_b = 0.177 m/s.

Replacing the constant value of κ is more awkward. We could describe Wilkie's curve (Fig.3.3.2.12) quite well by the equation

$$\kappa = \kappa_0 + \beta_\kappa F \qquad (4.4.9)$$

with compatible values: κ_0 = 39 000 N/m, β_κ = 100 m^{-1}. The trouble is that this equation only represents the case $\zeta = 1$ and as mentioned in Sec.3.3.3, we do not know what happens at other values of ζ. Anyway, this equation will have to be used whether it is right or not.

Combining equations 4.4.8 and 4.4.9, we have the non-linear equation for muscle properties:

$$\dot{F}_j(t) = \{\kappa_0 + \beta_\kappa F_j(t)\}\left\{\frac{F^M\zeta_j(t)+\beta_a}{F_j(t)+\beta_a} - 1 + \frac{\dot{\lambda}_j(t)}{\beta_b}\right\}\beta_b \qquad (4.4.10)$$

which replaces equ.4.4.6. Repeating the previous simulation, but with the new equation, we get the result shown in Fig.4.4.1.2 (Program 4-3).

Again, the result of our simulation has turned out to be unrealistic. The only explanation now is that there is a flaw in the data used. The curve of $G(t)$ versus t obtained by Wilkie is presumably accurate, and there is little reason to suspect Wilkie's viscosity curves, as they are based on a simple piece of theory and many measurements were taken by Wilkie. The culprit may be his curve of the elastic component. In fact, in his paper, Wilkie plots not stiffnes but its reciprocal, namely compliance, against force, and he obtains this curve from the formula

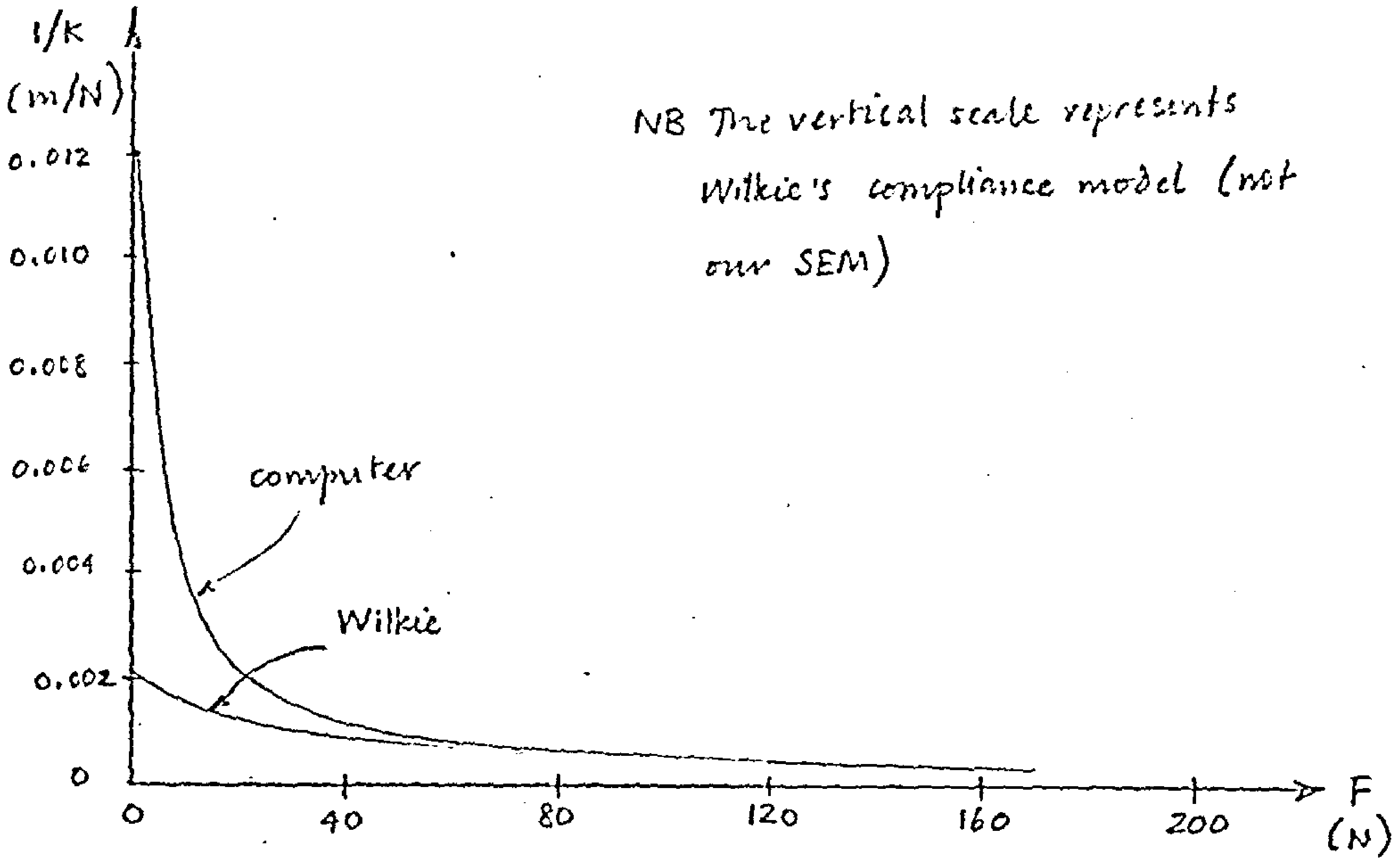
$$1/K = \left\{ \frac{F^M + \beta_a}{F(t) + \beta_a} \beta_b - \beta_b \right\} \Big/ \dot{F}(t) \qquad (4.4.11)$$

where the values of $F(t)$ are taken from the curve of $G(t)$ versus t, suitably scaled. To check the compliance graph, this formula was reworked by computer (Program 4-4) with 30 values of F taken at equal intervals throughout the rise in the experimental curve. The result is shown in Fig.4.4.1.3 and is clearly very different from Wilkie's curve at low values of $F(t)$. Now in fact it is almost impossible to take the first few measurements from Wilkie's curve of $G(t)$, as reference to Fig.4.4.1.1 shows, and it is simply a matter of opinion as to what these low values are (depending mainly on whether one considers the curve to be a continuous or discontinuous function at the origin). This seems to be a likely explanation of why the simulated curve of $G(t)$ differs so much from the original - the curve at low values has a great influence on the overall rise time of the curve.

In view of this discrepancy, the only safe way of obtaining realistic values for the muscle parameters is to approximate Wilkie's curve of $G(t)$ by an exponential curve - this enables us to use simple linear components as originally proposed. Suppose we choose the equation

$$G(t) = 196 \left[1 - \exp\left\{ -t/(-0.06/\log_e 0.5) \right\} \right] \qquad (4.4.12)$$

which coincides with Wilkie's curve at the point where $G = 100$. The two curves are compared in Fig.4.4.1.4. The exponential



NB The vertical scale represents Wilkie's compliance model (not our SEM)

Fig. 4.4.1.3

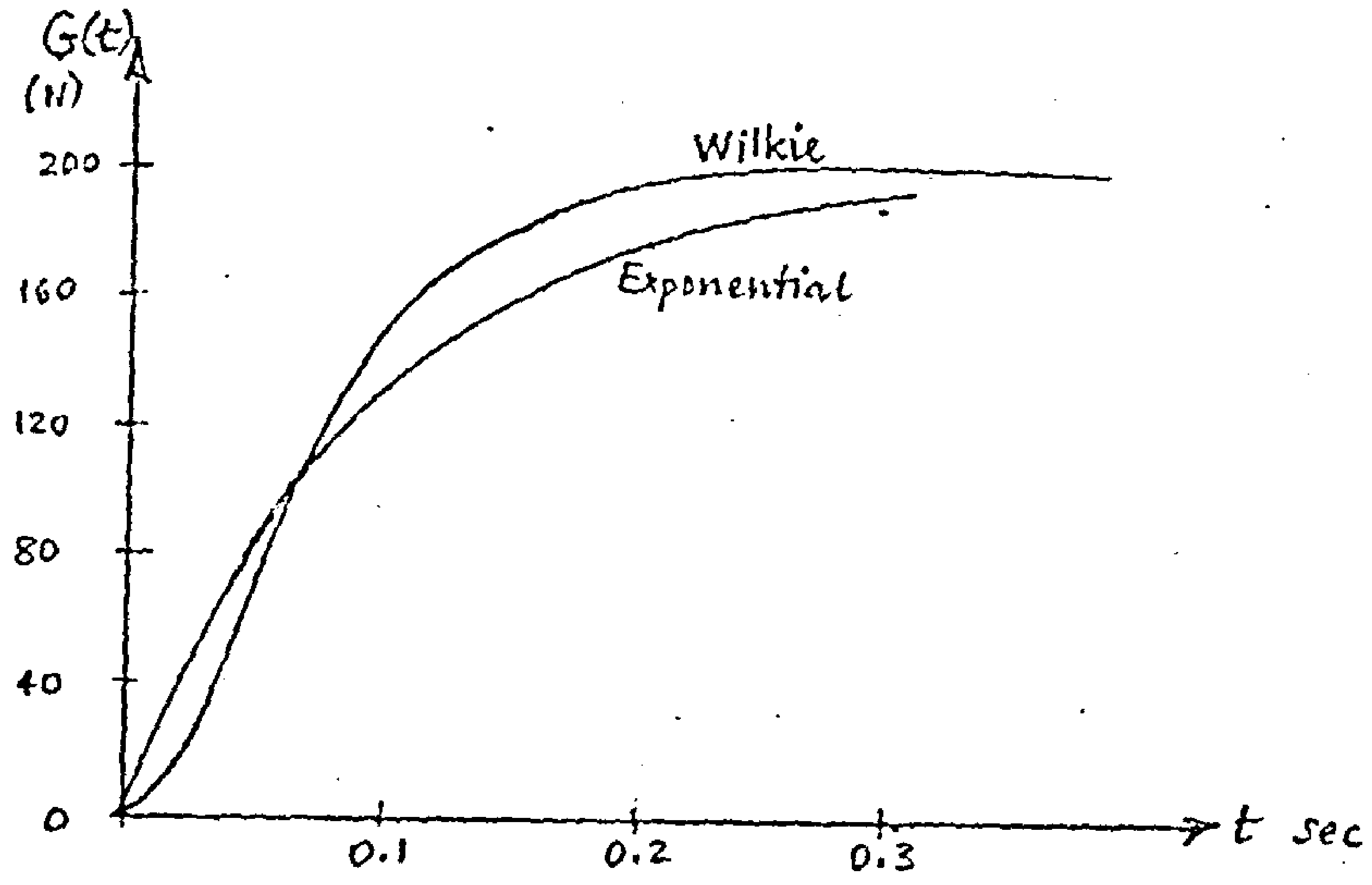


Fig. 4.4.1.4

curve has a time constant τ of 0.0866; taking $\tau = \mu/\kappa$, and linearising the viscosity curve of Wilkie himself (as opposed to the other subjects), we obtain (scaled to our SEM model)

$$\mu = 1940 \text{ Ns/m} \qquad \kappa = 22400 \text{ N/m}$$

To summarise: the muscle model used from here onwards is a linear component approximation to the muscle group of Wilkie himself, with stiffness κ and viscosity $\zeta\mu$ (where κ and μ have the above values), and its maximum strength is my own ($F^M = 1600$N). The relevant equation is equ. 4.4.6.

4.4.2 Simple Oscillation

Suppose that we now compare our new arm/muscle model with the arm/moment model of Sec.4.3 under the same conditions of oscillation - this will enable us to judge how much muscle properties affect movement. The position of the upper arm now affects the results, so let us make the additional condition that the upper arm is vertical. If we want the forearm to describe an oscillation which takes its tip between 0.5 cm above and 0.5 cm below its horizontal position, then we should try the following muscle switching signals:-

$$\zeta_1(t) = \begin{cases} 0 & \text{over positive intervals} \\ \zeta & \text{over negative intervals} \end{cases}$$

$$\zeta_2(t) = \begin{cases} \zeta & \text{over positive intervals} \\ 0 & \text{over negative intervals} \end{cases} \qquad (4.4.11)$$

where the intervals have the same definition as in Sec. 4.3, and ζ is the level of stimulation which will give the right amplitude of oscillation.

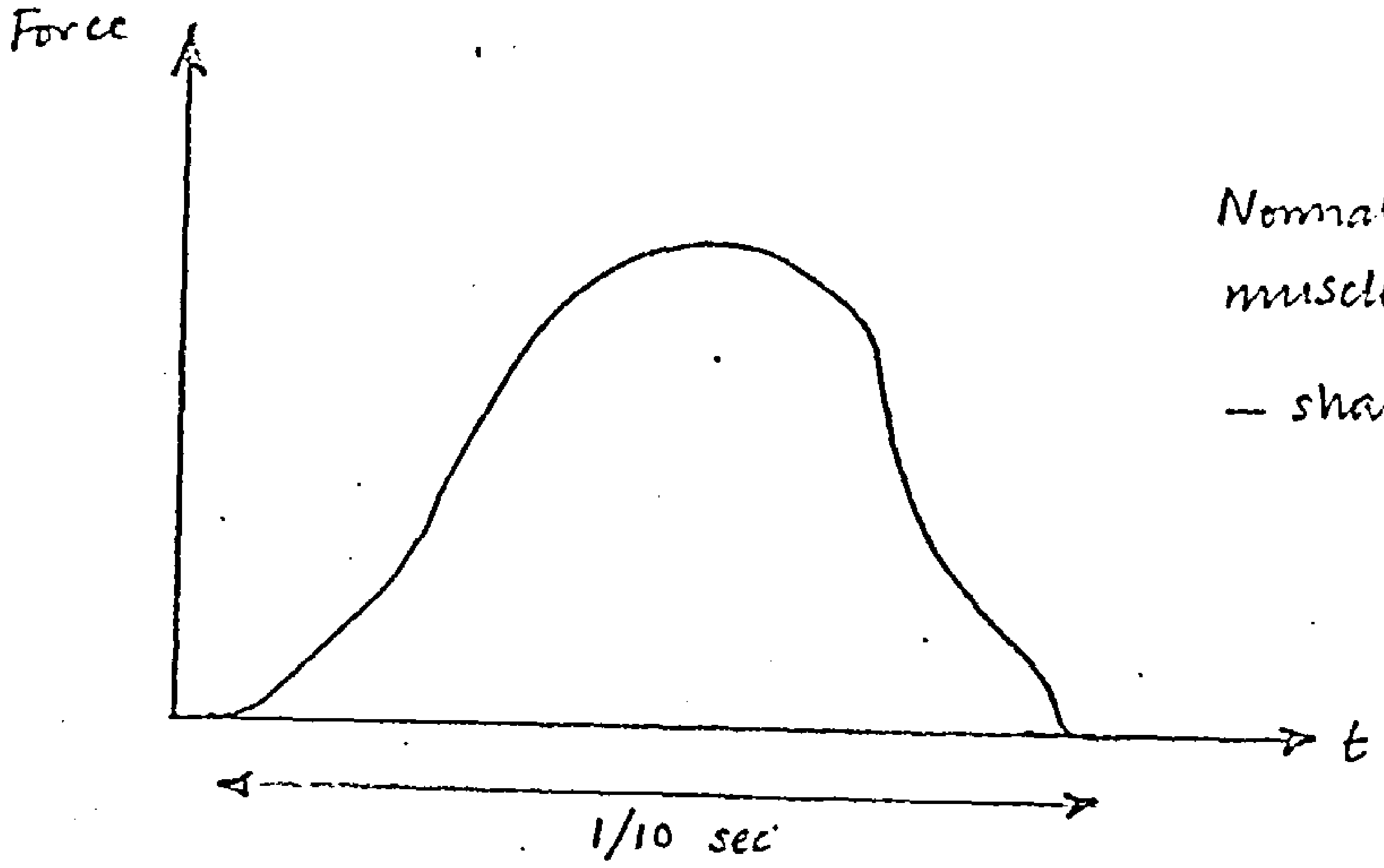
Simulation of the arm with these values (Program 4-5) gives an oscillation which drifts in a rather similar manner to the curve of Fig.4.3.5; clearly the passive muscular properties are enough to upset the stability of oscillation. At a frequency of 10 Hz, such an oscillation with an amplitude kept in the region of 1 cm is produced with a ζ of only 0.02; that is, according to the simulation, only 2% of the force available need be used to vibrate the forearm at 10 Hz.

Now at this stage we must examine the capabilities of a real arm under the condition of rapid oscillation. Suppose we turn to the literature of piano playing. Although on most topics, the writers we are considering totally disagree, there is almost complete unanimity over the state of antagonistic muscles during rapid oscillation. Matthay is the chief exception, preferring to avoid any mention of muscular effort. Amongst the other writers, Breithaupt, Ortmann, Fielden, Schultz and Gat all use the word "vibrato" in their discussions. Here are some extracts from their descriptions of the state of vibrato:-

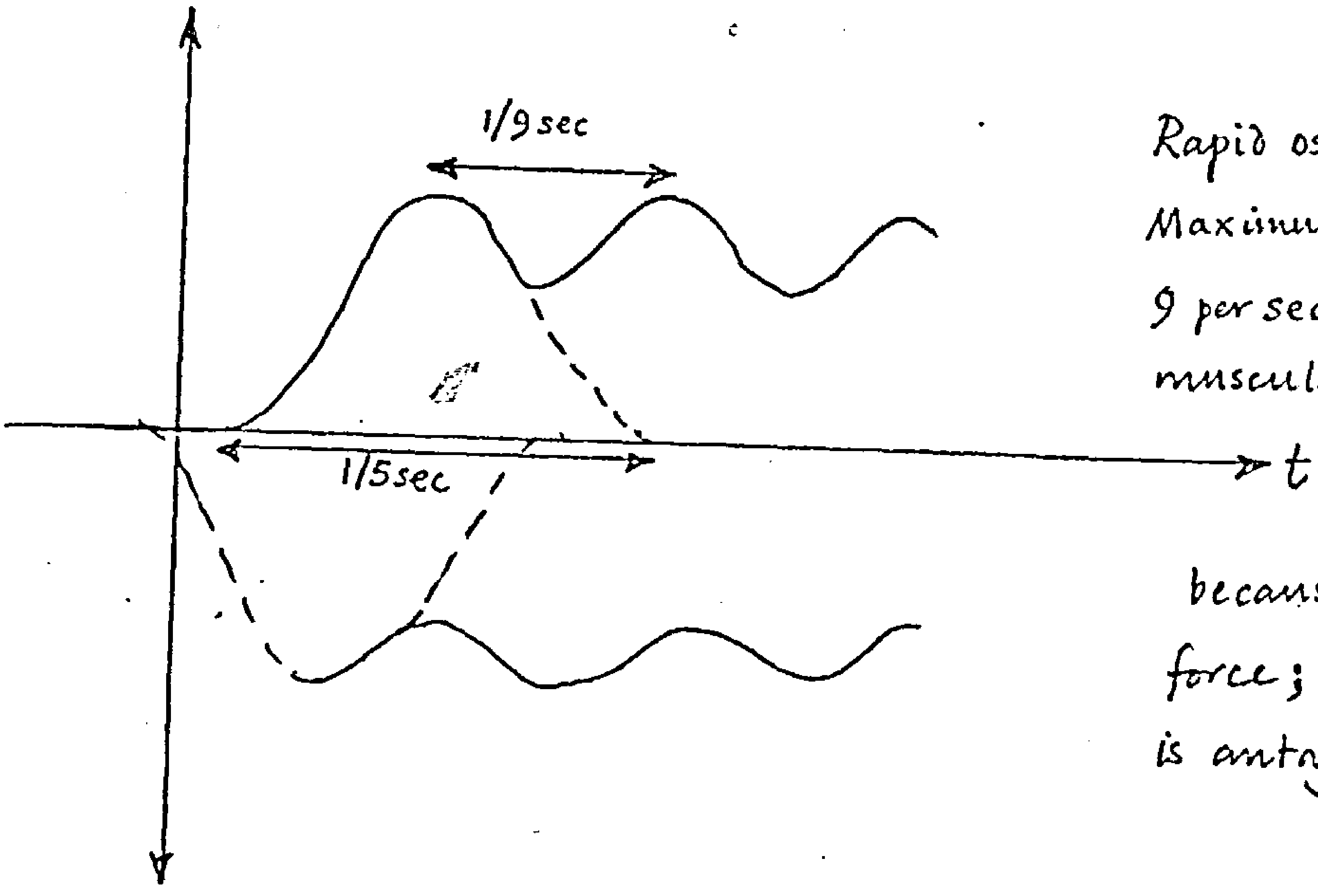
> Gat: "a special technique"; "tense movement of the forearm"
>
> Schultz: "requires simultaneous contraction of muscles" (i.e. antagonistic muscles)
>
> Fielden: "a state of fixation (or tension) of whole groups of muscles"
>
> Ortmann: "state of hypertension"; "demands utmost rigidity"; "continuity of muscular contraction"

Ching does not use the word "vibrato", but describes very clearly what, in his opinion, is the only way in which a rapid oscillation of the forearm can be produced. He says that because of the limitations of the muscle-nervous system both antagonistic sets of muscle groups at the elbow must be used simultaneously; that is, one group must switch "on" before the effects of the opposing group have had time to die away. Furthermore, in order to achieve the maximum rates of oscillation (he gives a ceiling of about 8 or 9 Hz), every ounce of strength in the muscles must be used. The situation, as Ching sees it, is depicted in Fig.4.4.2.1. Gat, Fielden and Ortmann also agree that a great deal of strength is necessary. Only Schultz is of the opinion that moderate strength is sufficient, but, unlike the other writers, he bases his decision on an intellectual argument, and we will see later that Schultz's powers of analysis leave something to be desired.

This unexpected solidarity amongst Gat, Fielden, Ortmann and Ching (and partly Schultz) is impressive. From my own experiments, I think that on this matter they are absolutely correct. But what about our model? It has failed miserably to depict the condition of vibrato. We are reluctantly forced to the following conclusions. Either (1) the mathematics of arm movements in this thesis has been bungled; or (2) the viscosity measured by Wilkie has little effect in reducing the speed of rapid forearm oscillation. If we (optimistically) accept the second of these statements as being true, we must search for an explanation of why the rate of oscillation of the forearm is limited to about 8Hz. One obvious theory is that the nervous system simply cannot cope with anything faster; in other words, 8 Hz is the fastest rate at which the body can "think" - even subconsciously. The objection to this theory is that it in no way explains why the muscles should have to work at maximum effort to achieve such a speed. It seems that something more complex is involved, and some suggestions can be made. Firstly, we can see that the mechanical properties of muscles are, in a sense, in a runaway position in that viscosity, in a model based on the papers of Wilkie and Bigland & Lippold, is proportional to the muscular stimulus; viscosity, by its resistance



Normal action of muscle (impulse) – shape not critical



Rapid oscillation of arm, Maximum rate about 9 per sec. Base of muscular impulse must extend to 1/5 sec because of increased force; therefore there is antagonistic contraction.

Fig.4.4.2.1. Ching's view of rapid arm oscillation.

invites more muscular stimulus to overcome it, and this in turn causes more viscosity. It is possible that this effect has some bearing on the case. Secondly, the measurements of Wilkie and Bigland & Lippold are taken under steady state conditions, i.e. at constant velocity, and it does not necessarily follow that they are suitable for describing a rapid oscillation; in the latter case there may be further variables such as limiting static friction and hysteresis effects which create added resistance to movement. Indeed, it is conceivable that the viscosity of reversed motion, discounted in Sec.3.3.3, comes into play during rapid oscillation. Thirdly, it may well be that the elbow joint does not take kindly to being rattled about at 8 Hz; after all, two large bone structures come into contact at this point, and the bones must at all costs be protected from any form of damage. Perhaps a large amount of antagonistic muscle force is necessary to give stability to the joint by pressing the bone surfaces together. Fourthly, one cannot help but think that the flabby state of the muscles at low levels of stimulation is highly relevant; but - let the investigator beware - Wilkie's curve (Fig.3.3.1.4) shows that, regardless of the physical state of the muscles, plenty of force is rapidly available.

4.4.3 More Feasible Switching

In Sec.4.3, two points were made. The first was that at high rates of oscillation, one could not expect input signals to the muscles to be perfect step functions. The second was that, because of this imperfection, some muscles were probably used purely to stabilise the oscillation. Suppose we now discuss the second point in terms of our model.

To begin with, let us take the idea of using some muscles for oscillation and some for stability. There are two distinct possibilities. Firstly, we could consider a pair of single muscles in antagonistic positions which switch on and off alternately, as in the previous section, with the remaining muscles, which are also arranged antagonistically, being used for positioning. The trouble with this arrangement is that it is still necessary to have a good synchronisation between the switching muscles. It seems very likely that these muscles would rapidly become out of phase with their desired waveforms, with the result that the amplitude of the oscillation would be uncontrolled; the positioning muscles would not be able to correct this satisfactorily. Of course, there may be a special phase-locking mechanism in the nervous system, but what seems more likely is the second possible arrangement. This is that the whole of one muscle group switches and the opposing group positions; in this way neither switching nor positioning is done antagonistically. (In terms of our model, $\zeta_2(t)$, say, equals one over positive intervals and zero over negative intervals, whilst $\zeta_1(t)$ remains in the vicinity of 0.5). The advantage of this is that there is no problem of synchronisation between opposing muscles, and yet positioning is still provided. Whether it is possible for all the muscles in a group to switch en bloc is a question which would need investigating. However, if group switching is not possible, an oscillation could still take place with one muscle switching and all the rest positioning.

The limitation of switching just discussed does have some relevance to the condition of vibrato, but it does not provide an explanation of why the condition occurs.

4.4.4 Increasing Strength

It is very much in the interests of a pianist to be able to develop as much as possible his faculty for rapid arm oscillation, as should be clear from reading Chap.1. Now we have seen that the maximum frequency of oscillation attainable depends, amongst other things, on the maximum strength available, at least, according to the theories outlined in Sec.4.4.2. Therefore, in order to increase his maximum frequency, a pianist should, on the face of it, develop the strength of his muscles. It is recognised, in the theory of athletics, that there are two distinct ways in which muscles can be made more powerful. Firstly, there are isometric exercises in which a muscle is flexed against a fixed resistive force. These are static exercises and are aimed at increasing the force output of a muscle for use in static or near-static situations (i.e. increasing F^M in our model). Secondly, there are isotonic exercises in which a movement is repeated rapidly, but without any kind of loading, save that of the body itself. These exercises are aimed at building resistance to fatigue by increasing the efficiency of the muscle to remove waste products. Isotonic and isometric exercises represent two extremes, and one can of course devise many exercises, let us call them "hybrid" exercises, which are a mixture of the two, for example, swinging Indian clubs..

There seems to be much controversy over which type of exercises athletes should practise. Take for instance the view of an expert in Karate. The object of Karate is to deliver large impulsive forces at high speed, and so is very relevant here.

Tegner (1963) in his book on the subject makes the rather surprising statement that isometric and even hybrid exercises are detrimental to ability in Karate, producing stiff and clumsy movements. On the other hand, consider the case of a popular isometric training device, the "Bullworker", used by Muhammad Ali and the German Olympics team. The makers of this device claim that isometric development can in no way impair mobility (one doesn't expect them to say otherwise). As for the books on piano playing, Gat and Fielden strongly recommend isotonic exercises and Ching strongly recommends both isotonic and isometric exercises (these latter exercises are specifically for improving oscillation frequency).

It is difficult to know what the truth is; certainly we cannot rely on our model to provide an answer. One factor in any analysis is that an increase in strength of a muscle results in an increased inertia of the link which carries it. But other factors must be considered. Most serious is the fact that the bloodstream system presumably will not be very much altered by an increase in muscle strength attained by isometrics. If a limb has more inertia, then more power is needed to drive it, therefore more chemical energy is needed and therefore muscular stamina is likely to be reduced because the bloodstream will have a comparatively greater load placed on it, - a nice problem in optimisation analysis. Furthermore, the analysis depends on the type of work a limb has to perform. It is well known that a 100 metres sprinter never has any stamina problem worth considering because the race is over before any kind of fatigue can set in. One possible conclusion from this is that a sprinter should be of a more muscular build than a long-distance runner, though one cannot have any degree of confidence in such a statement. However, comparison of a cheetah (a sprinter par excellence) against a typical man (comparatively a long-distance runner) tends to bear this out.

As for the pianist, the situation is very complex, as some stamina problems (for example, Ex. 7 of Sec.1.9) last two or three minutes, whereas in some cases explosive power is needed (Ex.26). I would guess however, that it is worth developing the arm muscles to somewhat above average strength.

In order to solve problems of strength, speed and stamina, it is necessary to have excellent data, and this does not seem to exist. It is interesting therefore, to note an article by Hill (Jimmy, not A.V., (1973)) who writes that Russian scientists, in searching for a male sprinter who would win them gold medals at the last Olympic Games, put information into a computer and produced the result that the sprinter should be exactly 5' 11½" and weigh 12 stone ! They then went out and looked for such a man. One wonders how the Russians reached such a conclusion; certainly vast amounts of data must be used if the job is to be done properly. However, as the man they found turned out to be Valeriy Borsov, one should reserve judgment.

4.5 INDIVIDUAL MUSCLES OF THE ELBOW

Having looked at the action of muscle groups as a whole, suppose we now turn to individual muscles. As mentioned in Sec.3.2, it seems to be generally accepted that there are two types of muscle acting on the elbow: "shunt" muscles and "spurt" muscles (MacConaill, 1946 and 1949). Let us now analyse this idea.

Suppose we take the upper arm to be fixed vertically and the forearm to be horizontal (This is the sort of posture considered by MacConaill). Consider first a muscle exerting a force F, acting mainly along the upper arm (Fig.4.5.1), and connected to the arm at distances a and b from the elbow as shown. Then the moment exerted by this muscle on the forearm about the elbow is $Fab/(a^2+b^2)^{1/2}$. Consider now a similar muscle lying along the forearm with the distances reversed as shown in Fig.4.5.2; the moment exerted by this muscle on the forearm about the elbow is $Fba/(a^2+b^2)^{1/2}$. These two moments are identical, and, therefore, the effect the muscles have on turning the forearm, whether it is loaded or not, is exactly the same in each case. One can only deduce from this that it makes no difference whether a muscle lies along the forearm or the upper arm - the amount of "spurt" in each muscle is the same. Taking the length of each muscle to be l , then the moment exerted by each muscle is

$$M = Fa(l^2-a^2)^{1/2}/l$$

Now as a varies M varies, and the stationary point, given by $dM/dA = 0$ is when $a = l/\sqrt{2}$, which means that a muscle is most effective in turning a joint when it lies between points at an equal distance from the joint. This is very different from

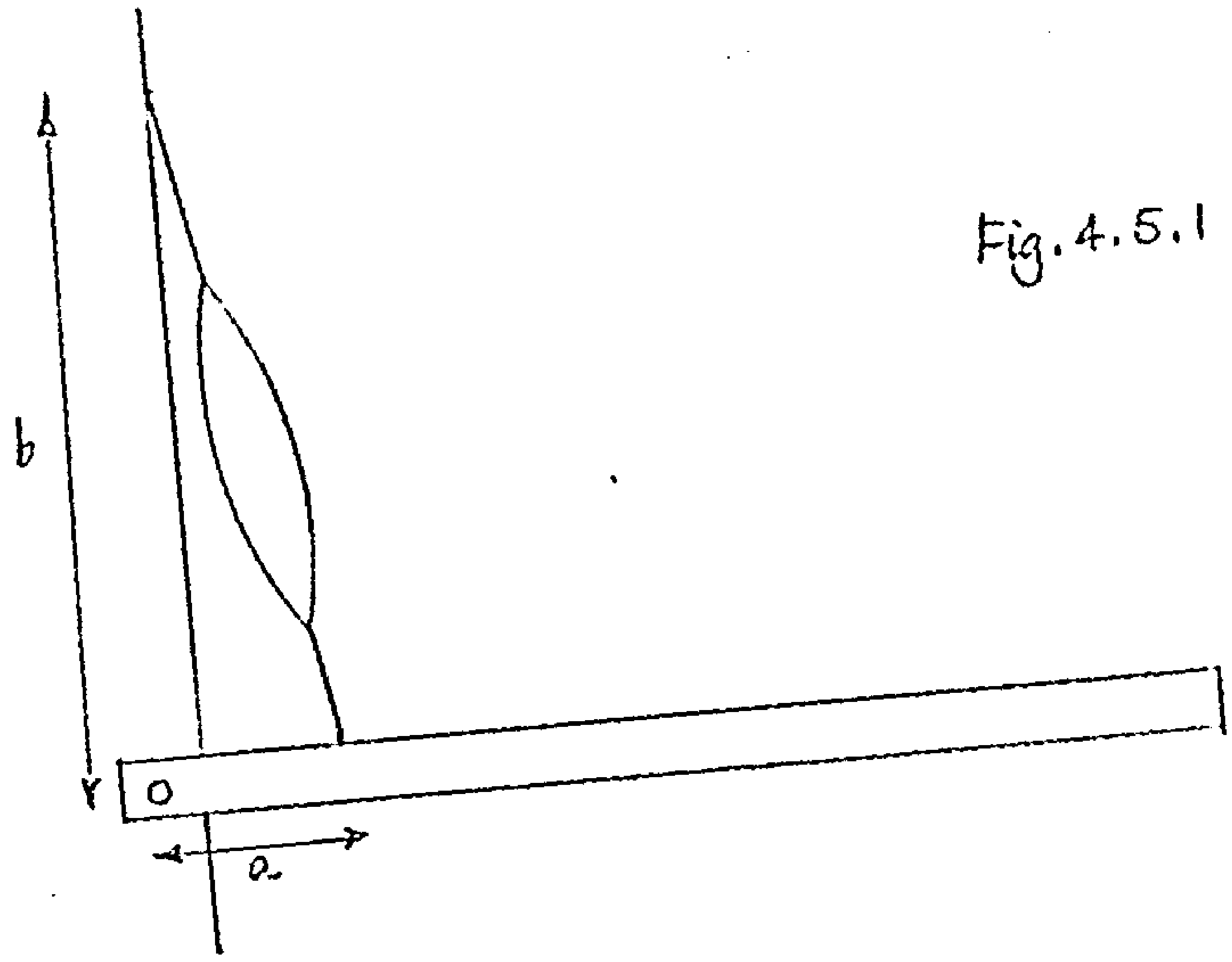


Fig. 4.5.1

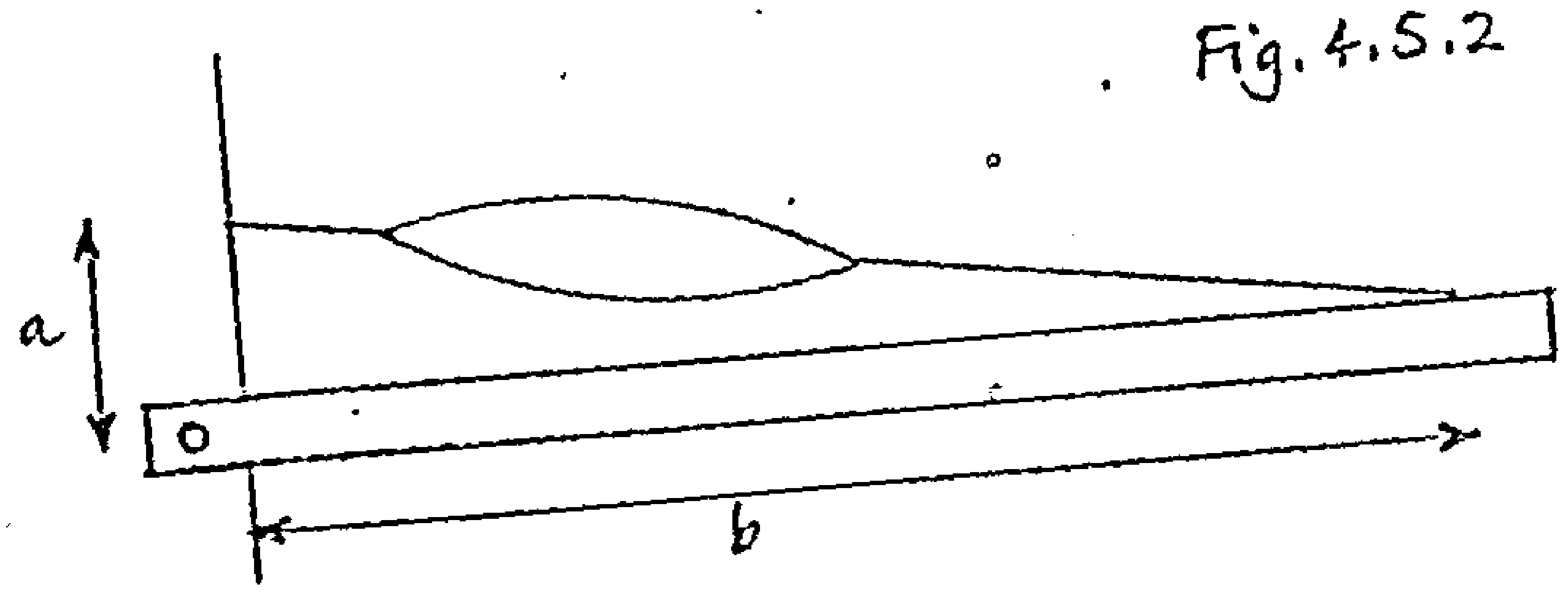


Fig. 4.5.2

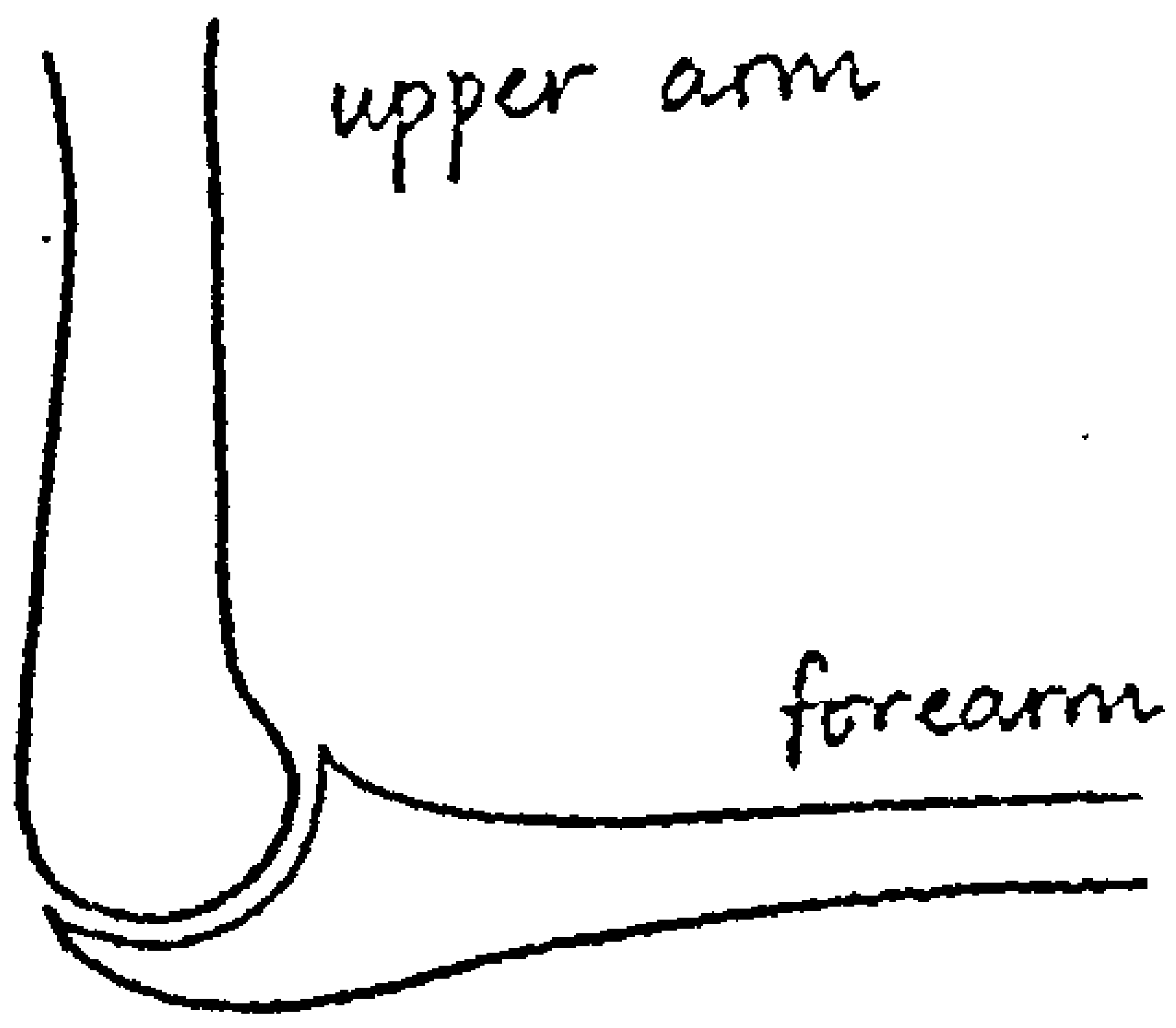


Fig. 4.5.3

what MacConaill says. Indeed there really seems no point in using the term "spurt muscle"; all muscles are effective in turning the joint.

But what about "shunt" muscles? If a muscle lies along the upper arm, then the reaction it produces at the elbow is almost vertical. If a muscle lies along the forearm, then its reaction is almost horizontal. Therefore, there is indeed a difference between the muscles as regards the direction of their "shunting" action. Now MacConaill describes a shunting action as a "stabilising" one because, he writes, under this action the surfaces of the joint are pressed together. In Fig.4.5.3, which is derived from reproductions of X-ray photographs in Gat's book, we can see that in the elbow joint the upper arm acts as a"ball" and the forearm as a "socket". Clearly, a forearm muscle, when it is tensed, presses the two surfaces together horizontally, and thus has a stabilising effect on the joint. But, for that matter, an upper arm muscle also has a stabilising effect. It does not matter whether the reaction is horizontal or vertical or in between, the surfaces of the joint are always pressed together, and the effect is therefore always one of stabilisation. Moreover, no matter what position the forearm is in, the same argument applies. We can only deduce from this that all muscles automatically have a "stabilising" effect.

We have seen that the terms "shunt" and "spurt" are pointless. It is interesting to speculate as to why MacConaill came up with such an idea. He seems to have been misled firstly by the fact that most muscles of the elbow have an anchor-like connection at one end, but a short tendon connection at the other. (These junctions are sometimes known as the "origin" and "insertion" respectively, and the muscles are said to "arise" from their origin). MacConaill seems to assume from this that force comes out of only one end of a muscle, namely the tendonous end. Here is part of the Summary of his 1949 paper: "Muscles which arise far from the joint are spurt muscles; those which arise near it are shunt muscles".

Secondly McConaill seems to have been misled by the fact that in circular motion about a fixed point, with fixed radius, there are two acceleration terms. He assumes from this that one muscle must "provide" one term, and the other muscle the other term, but this is just a red herring; the terms arise from the kinematics of the rotating body, and both muscles provide both terms.

Finally, MacConaill writes that shunt and spurt muscles may interchange their roles, depending on the action of the arm; for example, if the body is raised with the hands grasping a beam, then the roles of the elbow muscles are reversed. MacConaill writes in the Summary of his 1946 paper "Muscles which are prime movers when acting from their anatomical origins are joint stabilizers when acting from their anatomical insertions, and conversely". But surely this contradicts the previous quotation.

The concept of shunt and spurt muscles has spread through the literature. Basmajian makes considerable use of the idea and claims to have partly verified it for the elbow muscles. Gray's Anatomy, rather warily, says of the Brachioradialis, "It is particularly active in rapid movements, as opposed to the Biceps and Brachialis which show much more marked activity in slow flexion". However, a footnote attributes this theory to MacConaill and Basmajian.

Perhaps anatomists ought to be reminded that force actually comes out of both ends of a muscle, and that there is no difference between an origin and an insertion. It seems to me that the reason for the difference in the way the ends of the muscles are attached to the bone is simply that the angle of incidence is different.

This still leaves us with the question of why there should be muscles lying along both the forearm and the upper arm. Again I can hazard a simple explanation: a muscle serves the dual purpose of providing force and of protecting the bone, which is rather brittle; therefore the muscles should be distributed all over the arm. A further point is that the muscles of the elbow may be arranged so that as the elbow turns, then there is always at least one muscle working in a favourable range (see Fig.3.3.3.1).

4.6 JOINT RIGIDITY

The oscillations studied earlier in this chapter naturally give rise to a reaction at the shoulder. Now, the model used to describe the oscillations assumed the upper arm to be held unmoving. This is the same as saying that, if an oscillation is to proceed in a stable fashion (i.e. with the elbow stationary) then either the shoulder muscles must provide the appropriate action at the shoulder (properly synchronised), or the shoulder muscles must keep the upper arm in a permanently rigid condition. Now, in view of the remarks of Secs. 4.3 and 4.4.3, it does not seem likely that the shoulder muscles can synchronise themselves with the elbow muscles at high speeds, and so one must assume that if a fast oscillation is desired at a particular joint in the chain of segments that make up the upper limb, then the previous joints (the ones nearer the rest of the body) must be held rigid.

How is it possible for a joint to be made rigid? As each joint is equipped with a pair of antagonistic muscle groups, the answer would seem to be that the muscle groups both switch on and thus work in opposition to each other. At any rate, this is the view taken by Ching. Let us examine this mathematically.

Suppose we take the elbow model of Sec.4.4. As mentioned earlier the joint has very little friction; the notion of a rigid joint does not necessarily imply that the bone-joint itself is stiff. Suppose we consider the forearm to be held horizontal and subjected suddenly to a loading torque, G, acting clockwise. To gain some insight into which properties of the muscles provide the rigidity, let us take a series of different models of the muscles.

To begin with, suppose each muscle group consists of just a force-producing element of force $\zeta_j(t)F^M$. Before the load is applied, ζ_1 must equal ζ_2, otherwise the arm will move. No matter what preliminary value ζ_1 and ζ_2 have, when the load is applied the arm will sail round until ζ_1 and ζ_2 have been given new values to counteract the load. If the load is unexpected, this readjustment will be subject to a delay of the "reaction time" of Sec.4.0, by which time the arm will have gone a long way. If the load is expected, then the readjustment can be anticipated. However, this is now a question of applied psychology, and cannot be pursued here. We may conclude from this illustration that a force element alone is not sufficient to provide rigidity against unexpected loading.

Now suppose each muscle consists of a force-producing element in series with an elastic component. Then the elastic component will stretch according to the force produced. But this force is transmitted directly to the forearm, and, as the $\zeta_j(t)F^M$ elements produce forces which are not dependent on their lengths, we can see that the situation is effectively the same as before. Thus, the elastic components do not provide rigidity.

Suppose next that each muscle consists of a combined force-producing and viscous element. Then the equations of the system are:-

From equ.4.4.2:

$$p_1 F_1(t) \sin\psi_1(t) - p_2 F_2(t) \sin\psi_2(t) - G = I\ddot{\theta}(t) \qquad (4.6.1)$$

and for the linear-viscous muscle:

$$F_j(t) = \zeta_j(t) F^M - \zeta_j(t) \mu \dot{\lambda}_j(t) \qquad (4.6.2)$$

In addition, equs.4.4.1, 4.4.3, 4.4.4 and 4.4.5 are needed.

Now we can see that the viscosity of the system sets up a retarding force if the arm begins to move and so gives the joint a degree of rigidity. We can see further that this viscosity is controlled entirely by ζ_1 and ζ_2. When ζ_1 and ζ_2 are zero, there is no opposing torque to the load; when they are both unity, the loading is damped as much as possible. This is a beautiful piece of design by Nature as it means that damping control is provided more or less linearly by simple application of the muscle switching system.

As one of the muscles must be lengthened by the load, then it is likely that the higher viscosity of a stretched stimulated muscle (Sec.3.3.3) comes into play.

In this section we have shown that the viscous element of a muscle provides a joint with a certain amount of rigidity, provided that both antagonistic sets of muscles are switched on.

There may of course be other mechanisms to give rigidity to a joint; for example, the joint may be pressure-sensitive and withdraw its lubrication when the antagonistic muscles are used (this, incidentally, would provide another possible explanation of why so much force is necessary to produce a rapid oscillation.)

4.7 PREPARED MOVEMENTS

Suppose we are faced with the problem of moving one link of a limb as quickly as possible once only through a given straight line displacement. Reference to the literature of piano technique shows that Ching believes that the antagonistic muscles should be tensed prior to the movement, whereas Ortmann maintains that one muscle group only should be used, beginning with a sharp burst and then relaxing. Let us see what can be deduced from our arm model.

To begin with, Ortmann's view cannot be supported. If a movement has to be as fast as possible, then acceleration must be constantly applied, and it is therefore pointless to cut off muscle action during the movement. To check Ching's theory, however, careful investigation is necessary.

Suppose, then, we take our two muscle elbow model working in two different ways: (1) with $\zeta_1 = 1$ and $\zeta_2 = 1$ applied some 0.5 sec. before movement is due to take place (representing prior tension) and then with ζ_1 suddenly made zero; (2) with $\zeta_1 = 0$ and ζ_2 suddenly made unity. A simulation of this (Program 4-6) with $\theta(0) = 0$ gives the result that in 0.07 sec. the respective distances covered in the two cases are

(1) 1.7 rad (2) 0.5 rad

This result certainly vindicates Ching's theory, but it would not be wise to place a great deal of faith in such a simulation, as the model is very simple, and many factors are involved in making fast movements.

4.8 ROTATION OF THE WRIST

The wrist joint is clearly quite similar to the elbow joint as far as up-and-down movements are concerned, so it seems reasonable to extend the results of the analysis of the elbow to the wrist. There is one important difference, though, which is that, whereas the elbow parameters are independent of the state of the hand (apart from the value of the moment of inertia of the forearm and hand, which changes slightly according to hand position), the parameters of wrist movement are not independent of the state of the fingers. This can be demonstrated quite simply. If the fingers and thumb are spread wide apart, far more muscular force is needed to move the hand about the wrist than if the fingers and thumb are close together. The reason for this is clearly that the tendons (particularly those of the thumb) when stretched, create resistance at the wrist joint - this will become a familiar theme in later chapters. It is difficult to analyse this situation, and data no douht depends very much on the individual. However, as far as playing the piano is concerned, one can say that an oscillation at the wrist involving a wide stretch (for example, when octaves are played using a hand rotation) needs more strength than an oscillation where little stretch is needed (for example, when repeated thirds are played with the same fingers, using a hand rotation).

4.9 SUMMARY

In this chapter, the elbow has been studied, not with unqualified success. The rest of the thesis is concerned with piano playing, and makes use of some of the principles discussed in this chapter. The following terminology will be used: When the forearm moves in an up-and-down fashion this will be called "rotation", when it turns about its own axis this will be called "twisting" or "torsion". When antagonistic contraction is used at a joint, the joint will be said to be "rigid" or "stiff" at full tension, "relaxed" at zero tension, and "firm", or something similar, in between. ("Rigidity", of course is not absolute, but implies a state which is as near rigid as possible). When a portion of the arm is held virtually unmoving against loading it will be said to be in a "stable state".

5

SOME GENERAL CRITICISM OF PREVIOUS AUTHORS

5.0 INTRODUCTION

All this simulation is rather tedious, so perhaps this is as good a place as any in which to have a light interlude and take a closer look at the way in which the authors under consideration set about their analysis.

5.1 BREITHAUPT

Breithaupt does not delve into science, but relies on common sense and intuition. He uses words with the gay abandon of a true artist and is quite happy to consider mass, weight, pressure, force, energy, and so on, as all meaning effectively the same thing. By the end of this thesis one may well conclude that Breithaupt's approach is as good as any.

5.2 BREE

One can say little about Madame Bree's book. The descriptions she uses of her technical methods are so vague that they could mean almost anything. Furthermore, she has a philosophy that any technical difficulty should be magnified during practice - for example, the weak fingers should be made to work harder than the other fingers when practising in order to strengthen them. This is all very well, but one never knows whether the method she puts forward is that intended for performance or that for practice, the one method presumably being the exact opposite of the other.

5.3 MATTHAY

One of the chief difficulties in understanding Matthay's work is that Matthay, being of German descent, likes to begin all Important Words with Capital Letters. Thus he calls relaxation "Relaxation", and refers to his own overall method of piano technique, which involves the contraction of muscles, as "Relaxation". One does not need to be blessed with great perspicacity to see that this can lead to trouble. In fact, in general, Matthay likes to label a particular technical method with a name which is the reverse of the action proposed - for example, he has a theory that in the playing of finger passages (these are defined in Sec. 7.0), the forearm should not be rotated about its axis, but held in place torsion-wise by the arm muscles. He calls this principle "Forearm-rotation", and is extremely annoyed at Fielden for thinking that he means forearm rotation. (He goes on to explain, not altogether helpfully, that this Rotation may be "allowed to become visible as an actual rocking movement").

Matthay's methods of analysis fall into three categories. Firstly, there is the time-honoured "I can shout louder than you" form of argument, involving a liberal sprinkling of impolite comments. Secondly, there is the well-known method of argument-by-analogy, where we find Matthay explaining that because a tennis racket or a billiard cue is handled in such a way, therefore the piano should be similarly manipulated. Thirdly, there is a form of analysis which bears some resemblance to scientific method, where Matthay has tried to sort out the mechanics of the piano.

Ching, in reviewing Matthay's work, is perceptive when he says that Matthay seems to have confused weight with inertia and speed with acceleration. But, it seems further that, like Breithaupt, Matthay does not really distinguish between weight, pressure, mass, inertia, reaction, adjustment, "element", force, and so on. The trouble is that Matthay shifts his ground in a chameleon-like fashion. Whenever he is criticised he angrily replies that he meant something entirely different as any fool can see. In fact, it is impossible to pin Matthay down to any actual technical method. It is significant that a book has appeared (1948) with the title " What Matthay Meant".

5.4 FIELDEN

Fielden uses a certain amount of scientific theory, but is rather cautious in his deductions. However, he has a tendency to argue by analogy in just the same way as Matthay. Furthermore, Fielden's notion of the nature of force does not coincide with that of a scientist; for example, he describes the action of depressing a key as follows :

> "This precise point where the muscular resistance is "sensed" is the point at which any keyboard stroke, whether by finger, hand or arm, must be aimed. There is a theory in physical science that all inert masses have an upward thrust. The player must imagine that the keyboard has such an inertia with its upward thrust : and that the meeting-place of the two forces, the energy of the arm... and the upward thrust of the keyboard, is the point where the hammer hits the string... The fact that this point is resilient, not rigid, since it occurs in the course of key-descent.. and further, that the pressure on the double anchorage is muscular and therefore elastic, only serves to emphasize the importance of perfect timing of the feeling of resistance of the hammer ..."

This theory is then extensively developed, and forms the central part of Fielden's work. It seems to me that, like Matthay, Fielden wants to have his cake and eat it. He wants the muscles to contract, whilst being relaxed, the joints to be loose, whilst being held firm, and the key to descend with different speeds, independently of the force applied.

5.5 SCHULTZ

Schultz's book is by far the most difficult to deal with. In considering the basic finger actions needed to play the piano, Schultz goes into a great deal more detail than any of his colleagues. His arguments, too, when they are illogical (which they often are), are of an order of magnitude more subtle in their illogicality. One such case occurs where Schultz is reviewing Breithaupt's book. Breithaupt is very proud of a technique he presents for the playing of octaves, declaring it to give an amplitude level which is automatically held constant (a "brazen rhythmic tread" is Breithaupt's way of defining this). Schultz condemns the technique on the grounds that music should never be played at a constant level of amplitude, otherwise it would sound very dull. This criticism is obviously silly, but it is not so obvious where the fallacy lies. The explanation is that Breithaupt is aiming to control the amplitude level, firstly by achieving a constant level and then, presumably, by adding controlled fluctuations to this level. If a technique which gives automatic control of the amplitude level is abandoned, as Schultz demands, then the resulting music will no doubt sound interesting, but not for the right reasons, as control will have been greatly reduced.

Many other examples of illogicality could be given, but this one has been chosen because it gives the reader of this thesis a taste for the rather curious way in which Schultz argues. Indeed, this sort of juggling with words is Schultz's modus operandi, and his analysis of complicated dynamic systems is carried out entirely in words, so much force being assigned to such a movement, and so much to another, and so on, with never a number appearing. Really, no-one can hope to produce the right answer doing this.

And yet, Schultz is the most perceptive of all the writers. In his book he raises more questions than any other writer. What a pity he lacks the scientific ability to be able to answer them properly.

5.6 ORTMANN

Of all the authors reviewed here, it is Ortmann who is regarded by his colleagues (even Matthay) as being the scientist. At first sight, Ortmann's work does seem to be very scientific and absolutely comprehensive - anyone interested in the effect of strychnine on the pianist is clearly no ordinary writer. A closer examination, however, does not bear this out. For example, in his chapter on "Co-ordination and Inco-ordination", Ortmann attempts to describe the relationship between muscular force and the displacement of the arm (actually he is considering a typical $M = I\ddot{\theta}$ problem, although he does not write any equation). Instead of using calculus, Ortmann uses algebra, confusing average and instantaneous velocity in the process, and, not surprisingly, gets the wrong answer. Immediately afterwards we find the following extraordinary passage:-

> "The slower the movement the greater is the effect of the constant factors, heretofore ignored : atmospheric and joint-resistances, gravity, and inertia. Take the action of gravity, for instance, in a horizontal movement. Assume its numerical value to be 2. Its direction of pull, in a horizontal movement, will be at right angles to the line of arm-movement, and will tend to pull the arm down. If the movement lasts two seconds, gravity will exert a total force-effect of 2x2 or 4, the product of the numerical value of the force and the time through which it acts. If the movement lasts 10 seconds gravity will exert a total force of 10x2 or 20; five times as great as before. Again, assume the joint-resistance through the 30 inches of movement to be 60, the mass of the arm 10, and its acceleration 6. Since force equals the product of the mass and the acceleration, the force of the moving arm will be 10x6 or 60, sufficient to overcome the joint-resistance. Now suppose the speed of the same arm to be 2 instead of 6. Its force will then be 10x2 or 20, only one-third of the force necessary to overcome the resistance. At the same time gravity acts for a longer period and its force is correspondingly increased."

This is typical of Ortmann's analysis of mechanics. In general, he completely misunderstands the role of internal forces. He is also under the impression that the centre of gravity of the entire arm invariably resides at a point close to the elbow, irrespective of the posture of the arm. Ortmann has such faith in his mathematical ability that all his methods are based firmly on the results of his calculations, and so all his theories are simply incorrect, although by the laws of probability, some are more nearly correct than others.

But, perhaps most serious, one wonders just what Ortmann is investigating. Most of his investigations run on the following lines. Ortmann starts by describing a particular touch form (a "touch form" is a traditional technical stratagem), giving details of the appropriate movements and forces involved. He then gets an "experienced pianist" (we are not told whom) to use that touch form, and the resulting movements are recorded on a special piece of apparatus. In his book, Ortmann includes a photograph of this apparatus which shows a remarkably spindly construction using very long levers to leave a trace on a revolving drum. Clearly this mechanism has quite considerable properties of elasticity, inertia, friction and probably deadspace. This would not matter if the recorded movements were relatively slow, but Ortmann places great importance on very small fluctuations in his records - of the order of 1/100th second. Ortmann must also be criticised for leaving most of his theoretical graphs and recorded traces entirely unlabelled, so that one can only guess what they represent.

Really, Ortmann must be taken to task over this sort of approach. Either "experienced pianists" as a body play correctly, or they do not. If they do not play correctly, why is he observing them? If they do play correctly, why is he bothering to write a book which is clearly not intended for anyone other than an experienced pianist? The only way in which this approach could be justified is if all Ortmann's "experienced pianists" were in fact world-famous virtuosi, but if this were the case, surely he would name them? In short, Ortmann's book is not an investigation, but simply an observation.

It should be mentioned that these comments have been directed at Volume 2 of Ortmann's work, which is the "piano playing" part. Curiously enough, Volume 1 is as good as Volume 2 is bad. The reason for this is that simple experimentation and observation are quite sufficient for the subject-matter of Volume 1 and here Ortmann is within his depth.

Again, to be quite fair, a large section of Ortmann's second volume is taken up with a study of the differences which can occur in the physical construction of the arm. This part is very interesting, and seems quite accurate.

5.7 CHING

Ching, unlike most of the other writers, is capable of thinking logically and writing clearly. He is the only writer to get his scientific facts right. He relies on scientists to provide answers to his questions, which is a wise course; however, sometimes he seems to have misinterpreted their conclusions. He also has a tendency to copy the theories of Ortmann and Schultz, most of which are incorrect. His book would probably have been much better had he relied on his own judgment.

5.8 GAT

Gat, representing the Hungarian school of piano-playing, gives us an interesting goulash of logical thought and whimsicality. He sets off in fine style, quoting scientific works by Helmholtz, Pavlov, etc., and seems to have completely understood them. One is rather taken aback, then, to find him arguing as follows. After stating that the keys should never be depressed as far as the keybed, he continues :

> "In examining the sides of the keys of pianos used for at least four or five years, we find that the upper part of the wood of the keys is of darker colour. This proves that keys do not as a rule touch the keybed, otherwise their sides would have become uniformly dark".

(My criticism of this statement is that, firstly, the pianos were probably used only by Gat's pupils; secondly, a finger-tip is rounded at the end; and thirdly, the dirt on the sides of keys is due to the sideways movement of fingers which are changing position - a vertical finger action leaves no trace.)

One is, however, astonished at Gat's remarkable theories on how the piano key should be manipulated. Apparently the piano key should not be depressed downwards, as is commonly thought, but in fact depressed in an upward manner. He quotes (approvingly) an early German teacher who writes "The pupils should not strike the keys downwards".

The fact is that, for sheer vagueness, Gat is on a par with Matthay.

5.9 HARRISON

Harrison, realising what thin ice he is skating on, is very tentative in his proposals. As a result, one can find little to criticise. However, as Harrison's book is so short, his methods are not developed in any depth, and there is probably not sufficient information in the book to turn a student into a first class pianist.

5.10 IN CONCLUSION

The eleven books reviewed in this thesis total 2640 pages. After reading this chapter it should be clear that the job of trying to understand them is a hair-raising task. Illogicality and highly ambiguous terminology are difficult enough to deal with, but self-contradiction (which often occurs) makes life impossible. Nevertheless, there are pieces of good advice tucked away in these books which make them worth studying, and, wherever possible, the methods put forward in the books will be explained in scientific terms (or, to be more precise, what I <u>think</u> are the methods put forward). It must be accepted, however, that in some cases I simply have not been able to understand what the author is talking about.

6

THE PIANO KEY MECHANISM

6.0 INTRODUCTION

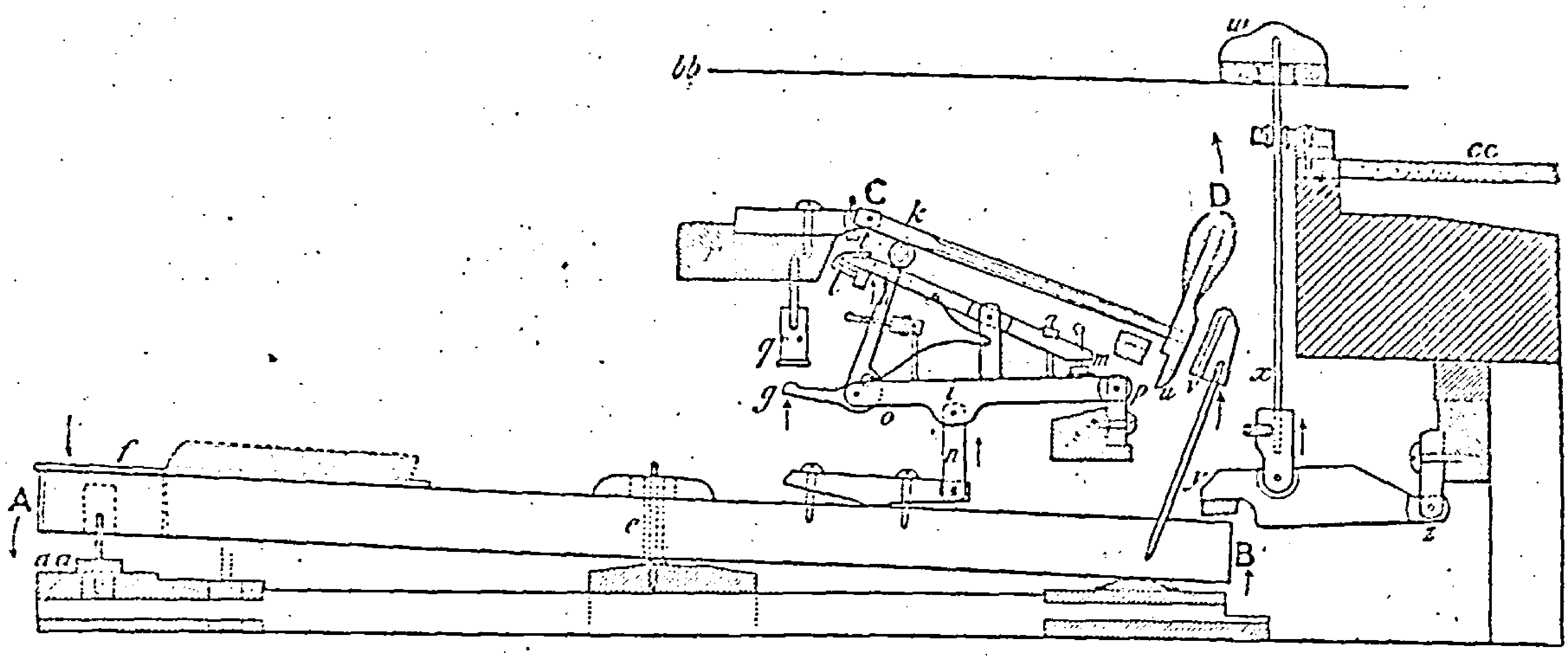
Having disposed of the basic biomechanical aspects of playing the piano we can now concentrate on the mechanism of the piano. In this chapter, the action of the piano is studied under the influence of an abstract force, that is, the piano is considered isolated from the arm.

As before, some computer simulations appear.

6.1 THE MECHANISM OF THE PIANO

On the next page is reproduced two pages from Matthay (1903) showing the action of each key of the piano. The description which Matthay gives is a good one. We can see from this diagram that the action has two different modes : the normal mode, and the repetition mode. In this thesis, the repetition mode will not be studied quantitatively because of the difficulty of mathematical representation; in any case, a study of the normal mode gives a good insight into the behaviour of the repetition mode.

FIG. 1.



DESCRIPTION OF FIG. 1.—The above Diagram forms an illustration of the best type of present-day "Grand-action"; it is a type now adopted as to its principles by all the great makers, although each has slight modifications as to details. It is from a tracing for which I am indebted to the great kindness of Messrs. C. BECHSTEIN.

We, as Pianists, should regard the whole of the mechanism from *A* to *D*, inclusive, as "KEY." The Piano-mechanic however often technically applies this term merely to the wooden rocker *A*—*B*. This rocker is pivoted at *e* and carries a finger-*plate* of ivory or ebony at *f*.

C—*D* is the "hammer" pivoted at *C*; it has a leather-covered "roller" attached to its underside at *k*.

r and *s* are *immovable* planks reaching across the full width of the key-board.

The compound ESCAPEMENT is formed by the two straight levers *p*—*o*, and *l*—*m*, and by the bent

lever or *L*-crank *g*—*h* (termed the "hopper") in conjunction with the before-mentioned "roller" attached to the hammer, and the adjustable set-off screws *q* and *t*.

The operation of the escapement is as follows:—

So long as the key remains unmoved, the Hammer rests, supported through its Roller *k*, upon the end *h* of the hopper: this latter being for this purpose passed *through* an aperture in the lever *l*—*m*, the "escapement-lever."

When the key is depressed, the whole of the levers concerned in the escapement are raised through the Upright *n*, and through them, the hopper-supported hammer.

Both the end *C* of the hammer, and the point *p* of the lever *o*—*p* however remain stationary, owing to their being pivoted to the planks *r* and *s*.

To prevent the hammer, on reaching the string, from "blocking" against it, the set-off nut *q* is so adjusted as to cause the hopper to tilt its *g*-end against this nut at the right moment. As the levers continue to rise while *g* is arrested by *q*, it follows that *h* slides from under the Hammer-roller, and as the rise of *l* has also been meanwhile arrested by the screw *t*, the hammer is thus left free to fall back. It cannot however, fall far away from the string, so long as the key is kept fully depressed, owing to its now resting on the lever *l*—*m*.

It is the latter lever that will enable us now to repeat the note without a full ascent of the finger-end of the key being previously required. For if the key is allowed to rise even slightly, then *h* will at once slightly descend, as will also the *m* end of the escapement-lever *l*—*m*; but as *l* is under a slight pressure from the spring underneath, it continues for awhile pressing *upward* against its screw *t* and thus holds the hammer still raised, though not in actual contact with the string. Meanwhile, a moment will however soon be reached, when the Hopper (actuated by the same spring that also gives life to the escapement-lever) will again be able to slip into position under the hammer-roller. We shall thus be able to repeat the note at will. The neat way in which the escapement-lever (*l*—*m*) thus as it were *lifts* and replaces the hammer upon the top of the hopper is a real marvel of mechanical ingenuity.

v is the Check; the *u* end of the hammer is caught by this on its recoil from the string.

w is the damper, lying on its string; and *y*—*z* is a little crank by which this is lifted through its wire *x* by the end of the rocker *A B* when the key is depressed.

At *aa* we also see the felt pads that prevent the key being taken down too far—the "key-beds" as they are here termed.

bb represents the position of the string.

cc, the edge of the sounding-board.

The arrows indicate the direction of the movements resulting from key-depression.

In the normal mode the action goes through three phases. Firstly the mechanism acts together as far as the moment of escapement, where point g reaches point q. At this moment, the hammer parts company with the rest of the mechanism and the action enters phase 2, in which the key proceeds to the keybed, and the hammer moves on a free flight to the string, rebounds from it and is caught by the check. The third phase occurs when the key is released, whereupon the action returns to its original position by gravity.

An important feature of the action is that escapement always takes place at the same point on the key descent - about 4 or 5 mm above the keybed. It must be said, however, that there is a possibility of an impact situation existing, in that an impact at the key surface may cause the hammer to instantly rise, without waiting for escapement. The situation can be artificially produced by holding the key and delivering a blow to its surface, but in actual playing the key is rapidly accelerated downwards and if the hammer had left prematurely, the rest of the mechanism would chase after it and almost certainly catch up with it.

6.1.1 Modelling the Piano Mechanism

We can represent the piano mechanism with a reasonable degree of realism by the arrangement of levers shown in Fig.6.1.1.1 Each small circle indicates the attachment of a link to a fixed point, and the double-headed arrows represent force transmission. This model makes the following approximations:-

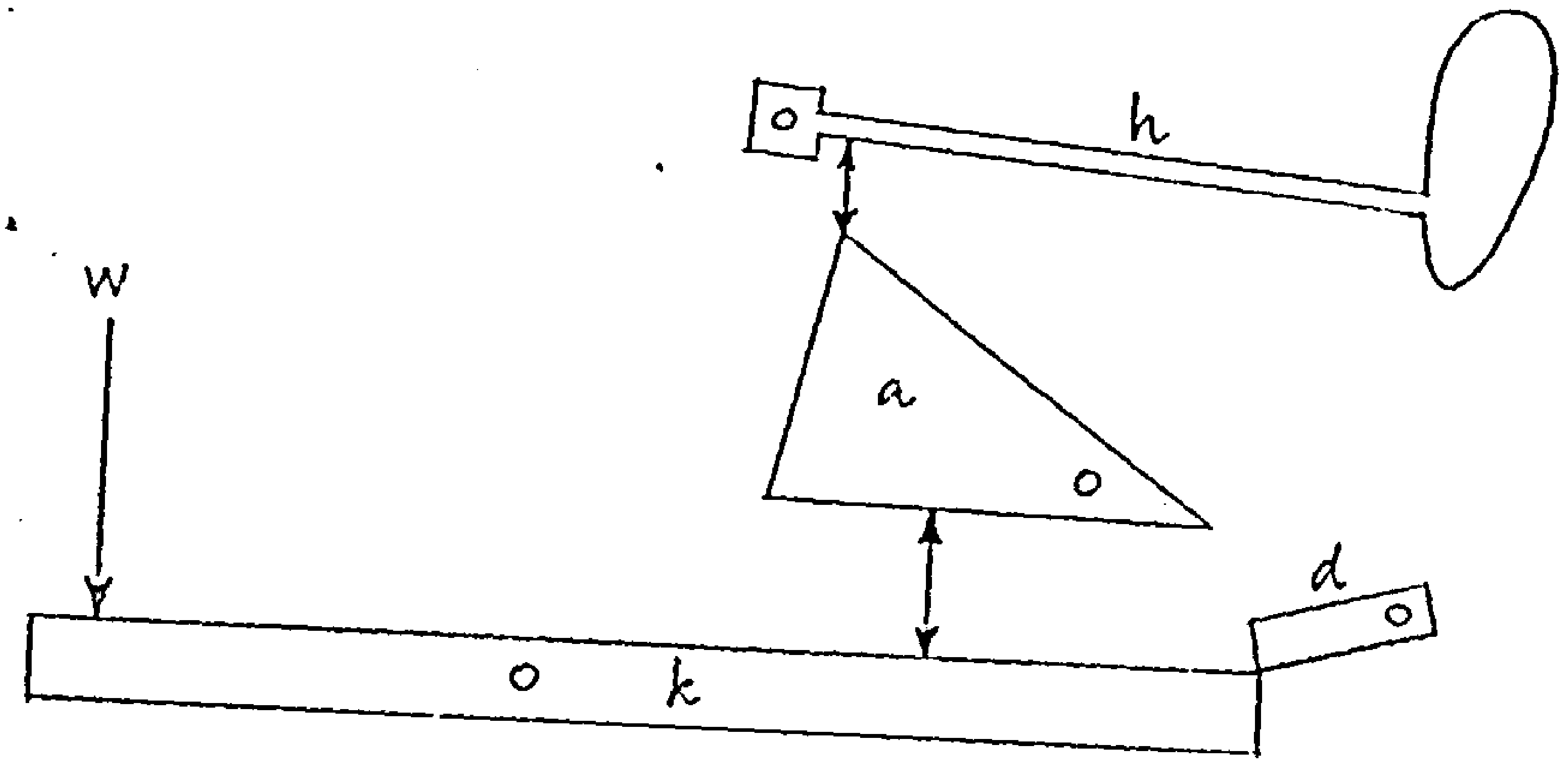


Fig. 6.1.1.1. The piano mechanism

1. The inertia of the escapement mechanism is replaced by that of a solid link. (In the simulations, a change of phase takes place automatically when the key has reached the point of escapement.)

2. The small and rather variable deadspace between the key and the damper is ignored.

3. The fulcrum of the key is considered to act at a point, whereas, in fact, there is a slight rocking action.

4. No friction has been taken into account; a piano should be kept in good order by lubricating the joints with some suitable material such as graphite.

5. The action of the roller probably has some qualities of "flicking" at escapement due to the roundness and resilience of the roller, and this is not accounted for.

These approximations are clearly quite reasonable. In the equations that represent this model, the following variables are used :-

m, I : mass and moment of inertia (about fulcrum) of a link.
ϕ : angular displacement of a link measured CCW from the horizontal.
d : horizontal distance between two points.
W : force applied to the key.
x_f : distance between W and the fulcrum of the key.
P : internal force.
t : time.
g : acceleration due to gravity.

The variables m and I are identified by a suffix from the set $\{k,d,a,h\}$, the members of which represent the links : key, damper, escapement mechanism and hammer, respectively. The variable ϕ has one suffix taken similarly and an optional second suffix taken from the set $\{0,b,e,s\}$, the members of which represent respectively the initial value, the keybed, the point of escapement, and the level of the string; e.g. ϕ_{hs} represents the angle made by the hammer as it reaches the string. The variable t has one optional suffix taken from the second set to indicate the instants at which points are reached. The variable P has two suffixes indicating between which links it acts. The variable d is always measured between the fulcrum of a link and either a point of contact between this link and another or the centre of mass of the link; the variable has two suffixes, the first indicating on which link the fulcrum lies, the second indicating either the other link or (letter "c") the centre of mass.

The equations of phase 1 are :-

$$\begin{aligned} Wx_f - P_{ka}d_{ka} - P_{kd}d_{kd} - m_k g d_{kc} &= I_k\ddot{\phi}_k \\ -P_{dk}d_{dk} + m_d g d_{dc} &= I_d\ddot{\phi}_d \\ -P_{ak}d_{ak} + P_{ah}d_{ah} + m_a g d_{ac} &= I_a\ddot{\phi}_a \\ P_{ha}d_{ha} - m_h g d_{hc} &= I_h\ddot{\phi}_h \\ -d_{kd}\ddot{\phi}_k &= d_{dk}\ddot{\phi}_d \\ -d_{ak}\ddot{\phi}_a &= d_{ka}\ddot{\phi}_k \\ -d_{ha}\ddot{\phi}_h &= d_{ah}\ddot{\phi}_a \end{aligned} \qquad (6.1.1)$$

It will be noticed that the relationship between the angular accelerations has been linearised. This is a further approximation, but results in a vast simplification of the equations. The above seven equations can be condensed into the two equations:-

$$\begin{aligned} Wx_f &= I_p\ddot{\phi}_k + c_p g \\ \ddot{\phi}_h &= \alpha\ddot{\phi}_k \end{aligned} \qquad (6.1.2)$$

where

$$I_p = I_k + \frac{d_{kd}^2}{d_{dk}^2} I_d + \frac{d_{ka}^2}{d_{ak}^2} I_a + \frac{d_{ka}^2}{d_{ha}^2} I_h$$

$$c_p = \alpha m_h d_{hc} + \frac{d_{ka}}{d_{ak}} m_a d_{ac} + \frac{d_{kd}}{d_{dk}} m_d d_{dc} + m_k d_{kc}$$

$$\alpha = \frac{d_{ka}\, d_{ah}}{d_{ak}\, d_{ha}} \tag{6.1.3}$$

The equations of phase 2 can be treated similarly, giving:-

$$\begin{aligned} Wx_f &= I_p' \ddot{\phi}_k + c_p' g \\ \ddot{\phi}_h &= -c_h g / I_h \end{aligned} \tag{6.1.4}$$

where

$$\begin{aligned} I_p' &= I_p - (d_{ka}/d_{ha})^2 I_h \\ c_p' &= c_p - \alpha c_h \\ c_h &= m_h d_{hc} \end{aligned} \tag{6.1.5}$$

(These equations do not represent the rebound of the hammer)

The equations of phase 3 are

$$\begin{aligned} 0 &= I_p \ddot{\phi}_k + c_p g \\ \ddot{\phi}_h &= \alpha \ddot{\phi}_k \end{aligned} \tag{6.1.6}$$

although to be absolutely strict, the values of I_p, c_p and α are very slightly different, owing to the different position of the hammer, during this phase.

So, despite their initial complexity, the equations take on a simple form. Now in evaluating the constants of the equations, we have the choice either of estimating the mechanical properties of each component and putting the figures together, or of evaluating the overall constants I_p, c_p etc. in some way. As there are so many components, accuracy would suffer greatly if the former method were used, and so the latter method is preferable. Data for the gravitational part of the equations, $c_p g / x_f$, was given in Sec.1.2, and a great deal of rather qualitative data is given in Ortmann (1925). A compatible set of data is given by Ching (1934) as follows:-

Force needed for the softest tone : 4 oz.+ 1 oz. Time taken:1/10sec.

Force needed for the loudest tone : 4oz.+ 225oz. Time taken:1/150sec.

where the quantity 4 oz. represents the gravitational part. As the quantities involved are only approximate, it is sufficient, for the purpose of evaluating the constants, to consider equs. 6.1.2 to apply throughout the whole descent. Using Ching's data with these equations gives $I_p \phi_{kb}/x_f$ = 140 kg.m and c_p/x_f = 0.11 kg. From Matthay's diagram of the piano we can measure the quantities:-

$$\begin{aligned} d_{ka} &= 0.12 \text{ m} \\ d_{ha} &= 0.014 \text{ m} \\ \phi_{ko} &= -0.021 \text{ rad} \\ \phi_{ke} &= 0.004 \text{ rad (approx)} \\ \phi_{kb} &= 0.021 \text{ rad} \\ \phi_{ho} &= -0.33 \text{ rad} \\ \phi_{he} &= -0.10 \text{ rad (approx)} \\ \phi_{hs} &= 0.05 \text{ rad} \\ x_f(\text{max. value}) &= 0.24 \text{ m} \\ \alpha &= 9 \end{aligned}$$

Examination of an isolated hammer provides:-

$$\begin{aligned} m_h &= 0.0115 \text{ kg} \\ d_{hc} &= 0.095 \text{ m} \\ I_h &= 0.00013 \text{ kg.m}^2 \\ c_h &= 0.0011 \text{ kg.m} \end{aligned}$$

Assuming x_f in Ching's data to be 0.24 m, we can deduce :-

$$\begin{aligned} I_p &= 0.0079 \text{ kg.m}^2 \\ c_p &= 0.027 \text{ kg.m} \\ c_p' &= 0.017 \text{ kg.m} \end{aligned}$$

Unfortunately, this mixed bag of data does not fit together happily (it gives a negative value of I_p'); if, however, we adjust the values slightly as follows :-

$$\begin{aligned} I_h &= 0.00010 \text{ kg.m}^2 \\ I_p &= 0.0100 \text{ kg.m}^2 \\ d_{ka}/d_{ha} &= 8.0 \end{aligned}$$

this gives the quite reasonable value:-

$$I_p' = 0.0036 \text{ kg.m}^2$$

6.2 SOME ASPECTS OF TONE AMPLITUDE

We saw in Chap.1 that a pianist is expected to play over a wide range of amplitude. As amplitude is so important, we should investigate the factors which affect it, and for this we can use our piano-key model. Throughout this section, suppose that the model is subjected to an applied force, W, at the tip of the key (so that x_f = 24 cm.), and that W has a constant value and is applied through the entire descent of the key, from key-surface to keybed.

The first stage in the investigation is to find the relationship between the applied force, W, and the angular velocity of the hammer as it hits the string, $\dot{\phi}_{hs}$. Fig.6.2.1 shows the result of such a simulation (Program 6). We can see from this curve that there is a parabolic relationship between $\dot{\phi}_{hs}$ and W and that there is a minimum force, W^{MIN} = 1.30 N, below which there is not enough force to enable the hammer to reach the string.

The next stage is to consider the effect of the hammer velocity on the amplitude of string vibration. Consider a wire of length $2L$ stretched between two fixed points with a tension of T. Now if a vertical upward force, F, is applied to the middle of the wire, the wire will be deflected through a very small angle, α, so that, approximately, $F = 2T\alpha$. If the vertical deflection of the wire at the point of application of the force is x, then $x = L\alpha$, and so $F = 2Tx/L$. In fact, a piano hammer does not hit its string(s) in the middle, as this would cause an undesirable mixture of overtones; nevertheless, the important point is that, in a stretched string, there is a linear relationship between force and deflection, and so we can

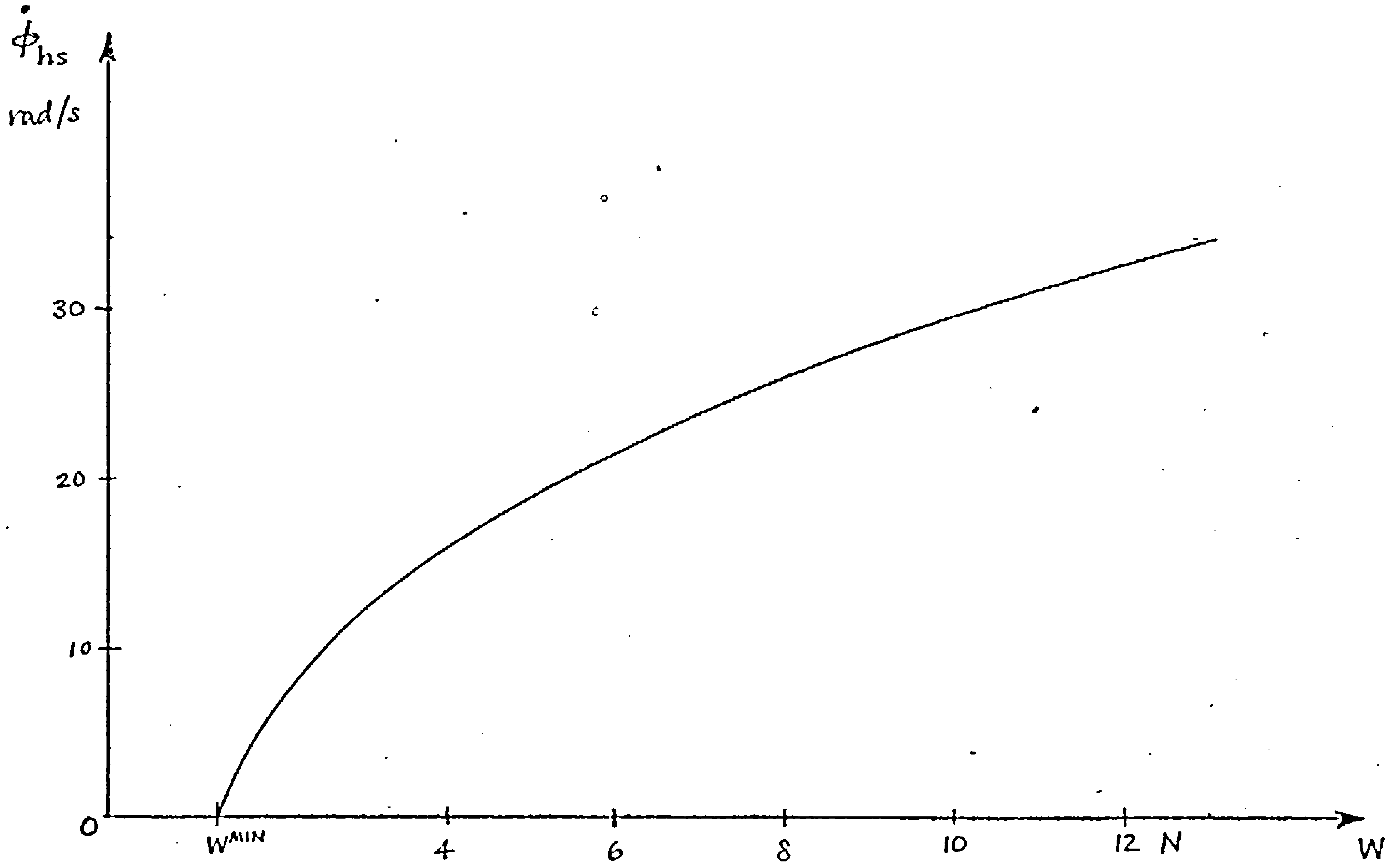


Fig. 6.2.1

write $F = kx$, where k is a constant.

Now if we consider the force F to be produced by a hammer of length r hitting the string, then the retarding moment provided by the string about the fulcrum of the hammer is $M = -Fr$. If the hammer is deflected through a very small angle $\delta\phi_h$ whilst it is in contact with the string (assuming the surface of the hammer to be hard), then $x = r\delta\phi_h$ and (neglecting gravity) $M = I_h\ddot{\phi}_h$ Hence $F = -I_h\ddot{x}/r^2$ and putting $I_h/r^2 = m$, we have

$$m\ddot{x} + kx = 0 \tag{6.2.1}$$

A solution of this equation is

$$x(t) = a \sin \omega t \tag{6.2.2}$$

where $\omega = \sqrt{k/m}$ and $a = \dot{x}(0)/\omega$. But $\dot{x}(0) = r\dot{\phi}_{hs}$, therefore

$$a = (r/\omega)\,\dot{\phi}_{hs} \tag{6.2.3}$$

These equations refer to the hammer-string system, which only exists for half of one cycle, but once the hammer has left the string, the string will continue to vibrate with the same amplitude. Thus the amplitude of vibration of the string depends linearly on the angular velocity of the hammer at the string.

The next stage is to consider the sound waves generated by the string. If the velocity of sound in air is V_S and the frequency of the string is f , then the wavelength of the sound wave, λ , equals V_S/f. Let us consider a narrow column of air, area Q and length λ , directly above the string and with the same width as the string. Now V_S = 340 m/s and the fundamental frequencies of the strings of a piano are all less than about 4000 Hz; furthermore, even the bottom strings only vibrate a millimetre or two at their maximum, so we may conclude that $a << \lambda$, which enables us to use the thermodynamic laws for a gas in differential form. The compression of a sound wave is virtually an isentropic process (Vennard, 1961) and can be described by the relationship : pV^n = constant, where p is pressure, V is specific volume and n is the adiabatic exponent. If p_0 and V_0 are the average pressure and volume of our column of air and δp and δV are the maximum perturbations in these quantities due to the vibrating string, then $(p_0 + \delta p)(V_0 + \delta V)^n = p_0 V_0^n$, and, expanding binomially to the first order,

$$\delta p = -(n p_0 / V_0)\, \delta V$$

and, as $\delta V = -aQ$, it follows that

$$\delta p \propto - a \tag{6.2.4}$$

After this, let us consider the vibration of the sounding board. There is some disagreement in the literature over what causes the board to resonate. One theory is that the frame of the piano transmits the vibrations of the string to the sounding board; a second theory is that the column of air between the strings and the sounding board couples the vibrations. Let us look at both cases.

First, suppose that the frame is the go-between. We may consider the frame and the sounding board to be a composite elastic body. At the ends of each vibrating string, a force - virtually a point force - is exerted on the frame. Now in the analysis of elastic behaviour, an important theorem is that small deformations are governed by the principle of superposition, which means, for instance, that the deformation at a point A is proportional to the force applied at a point B. It follows that the deflection of the sounding board is proportional to the force exerted by the string, which in turn is proportional to T, and hence the maximum deflection of the board is proportional to $\dot{\phi}_{hs}$.

Actually this argument is rather oversimplified, because it refers to a static deflection, whereas the sounding board exhibits a certain amount of resonance. However, there is not too much resonance, because if a string is damped, the board quickly stops vibrating; it seems reasonable therefore to accept the basic argument.

Secondly, suppose instead that the vibrations are transmitted through the air. Now a column of air of area Q between the string and the board sets up a maximum force on the board of $Q\,\delta p$, and therefore the maximum vertical deflection of the board b, is proportional to δp and hence $\mathring{a}$, which is the same conclusion as before.

As a result of this vibration transmission, the board as a whole sets up sound waves of amplitude $\delta p'$, and by the use of the gas law again it follows that $\delta p' \propto b$. The overall conclusion to be drawn is that there is a linear relationship between the angular velocity of the hammer as it hits the string and the maximum pressure differential of the resulting sound wave.

We still have to consider the sound waves travelling to the listener. Roughly speaking, we can take the piano as a point source of sound, emitting waves of initial pressure amplitude $\delta p'$, and the waves to spread from it spherically. Suppose we follow one wavecrest, say that part of a wave which is within a distance of $\pm\delta\lambda/2$ from the sphere of maximum pressure disturbance, where $\delta\lambda << \lambda$. The energy contained in this portion of the wave is approximately $4\pi R^2\,\delta\lambda\,\delta p''(R)$, where R is the distance of the wavecrest from its source and $\delta p''(R)$ is the maximum pressure disturbance at this distance. As this energy remains nearly constant whilst the wave travels through the air, it follows that $\delta p''(R) \propto 1/R^2$ for a given $\delta p'$, and hence in general

$$\delta p''(R) \propto \dot{\phi}_{hs}/R^2 \tag{6.2.5}$$

Now we saw in Sec.1.10 that the sensation of amplitude in the ear of the listener follows a logarithmic law, and hence it can be written

$$s = k \log_e (\delta p''/\delta p_t) \tag{6.2.6}$$

where δp_t is a threshold level, constant for a given person, and k is a constant. Therefore, for a listener sitting at a constant distance from the piano,

$$s = k' \log_e (\dot{\phi}_{hs}) - k_t \tag{6.2.7}$$

where k' and k_t are constants. (k_t is effectively the threshold level for hearing the piano at this distance). Now we saw earlier that, approximately, $W \propto \dot{\phi}_{hs}^2$ and therefore we can write,

$$s = (k'/2) \log_e W - k_t' \tag{6.2.8}$$

where k_t' is a new constant.

It is this equation which has been our target, as it shows the relationship between the applied force and the resulting aural sensation. We can define the function ds/dW as the "amplitude sensitivity" which is a measure of how much leeway a pianist has in trying to play at an even amplitude. To illustrate: if the pianist misjudges the force he applies by an amount δW, then the ear hears a bump of $\delta s = (ds/dW)\delta W$. From equ.6.2.8,

$$\frac{ds}{dW} = \frac{k'}{2W} \tag{6.2.9}$$

so we can see that the amplitude sensitivity is inversely proportional to W, which shows why it is so difficult to play both quietly and evenly. At any rate, one is rather taken aback by Matthay's advice that pianissimo playing "is your surest touch".

Ching seems to have been the only investigator to understand the highly nonlinear characteristics of the force-amplitude curve for the piano. However, Ching just gives the simple parabolic curve (Fig.6.2.1) and takes this to show that it is difficult to play quietly; as the physical amplitude of the sound wave, $\delta p''$, is proportional to $\dot{\phi}_{hs}$, he is at first sight correct. But as we have seen, the true situation is more complicated; in fact it is the logarithmic characteristics of the ear which have the dominating influence on the force-amplitude curve – a logarithmic curve has a much greater curvature than a square-law curve. This is one reason why the properties of the ear cannot be neglected. In Sec.6.4, further reasons will appear.

This argument has always assumed the hammer to be non-crushable. In fact, it is covered with felt, but this felt becomes permanently flattened into a hard mass where it comes into contact with the string. Thus the argument in the main still holds, though clearly there are some complications in the immediate vicinity of the point of minimum force, W^{MIN}. Some elaborate mathematics to describe the elasticity of the felt under impact has been constructed by Ghosh (1936).

6.3 CONNECTIVITY

In Sec.1.7, four dynamic conditions were laid down: those of speed, amplitude, amplitude fluctuation and connectivity. We have just discussed amplitude; suppose we now turn to connectivity.

The production of notes on the legato side of the connectivity spectrum depends on pedalling, the overlapping of finger actions and the surrounding acoustic conditions - there is little controversy over this. The production of staccato notes however demands a special finger or arm action, and writers are by no means in agreement as to which action produces the best staccato. In this section, the basic key mechanism model is used to illustrate the basic facts of staccato playing.

Suppose we look at a typical descent and ascent of a key. Fig.6.3.1 shows the result of a simulation (Program 6) in which $W = 1.40$ N (this produces a tone of low amplitude) and in which the finger (or to be precise, the abstract applied force W) is supposed to rest on the keybed for 0.1 sec. after which it is promptly removed. The crux of the matter is the actual time during which the note sounds. This lasts from the moment that the hammer strikes the string, t_s, until the moment the damper falls, t_d (the falling of the damper is not represented in the equations of the model, but it can easily be added to the diagram).

If we want to produce a note which is as staccato as possible then we must make the duration of the note as short as possible. Consider for the moment that the key is taken down to the keybed, as in the simulation. We can see immediately that in this case the key should remain on the keybed for as little time as possible. But what about the ascent time - can this be shortened? The answer is no, because the key returns by gravity; indeed, if the finger is not very smart in removing itself from the key, this ascent is likely to be impeded. This leaves us with the descent time to try to alter. Most writers take the view that staccato playing is mainly a question of delivering a sharp acceleration

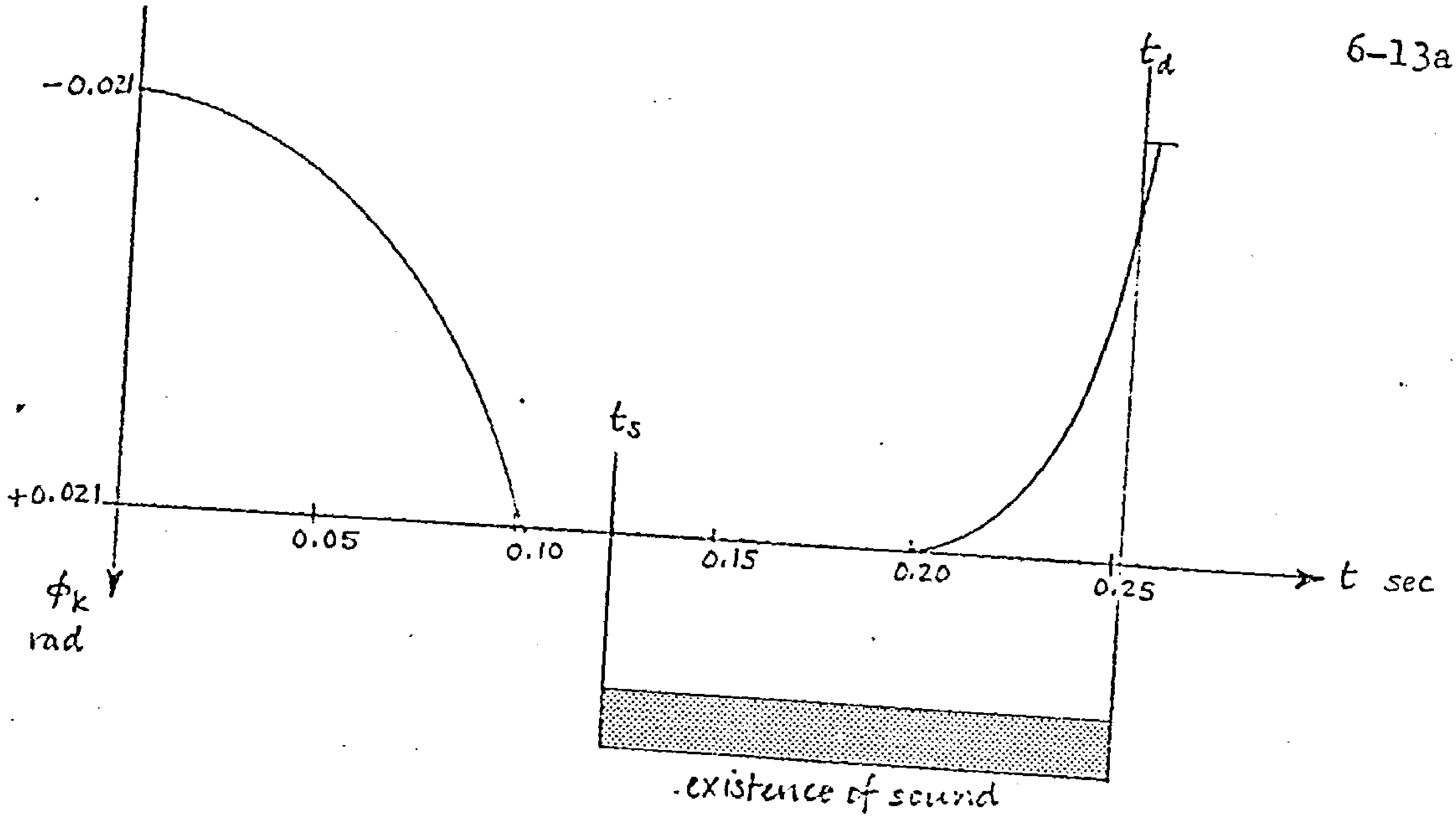


Fig. 6.3.1

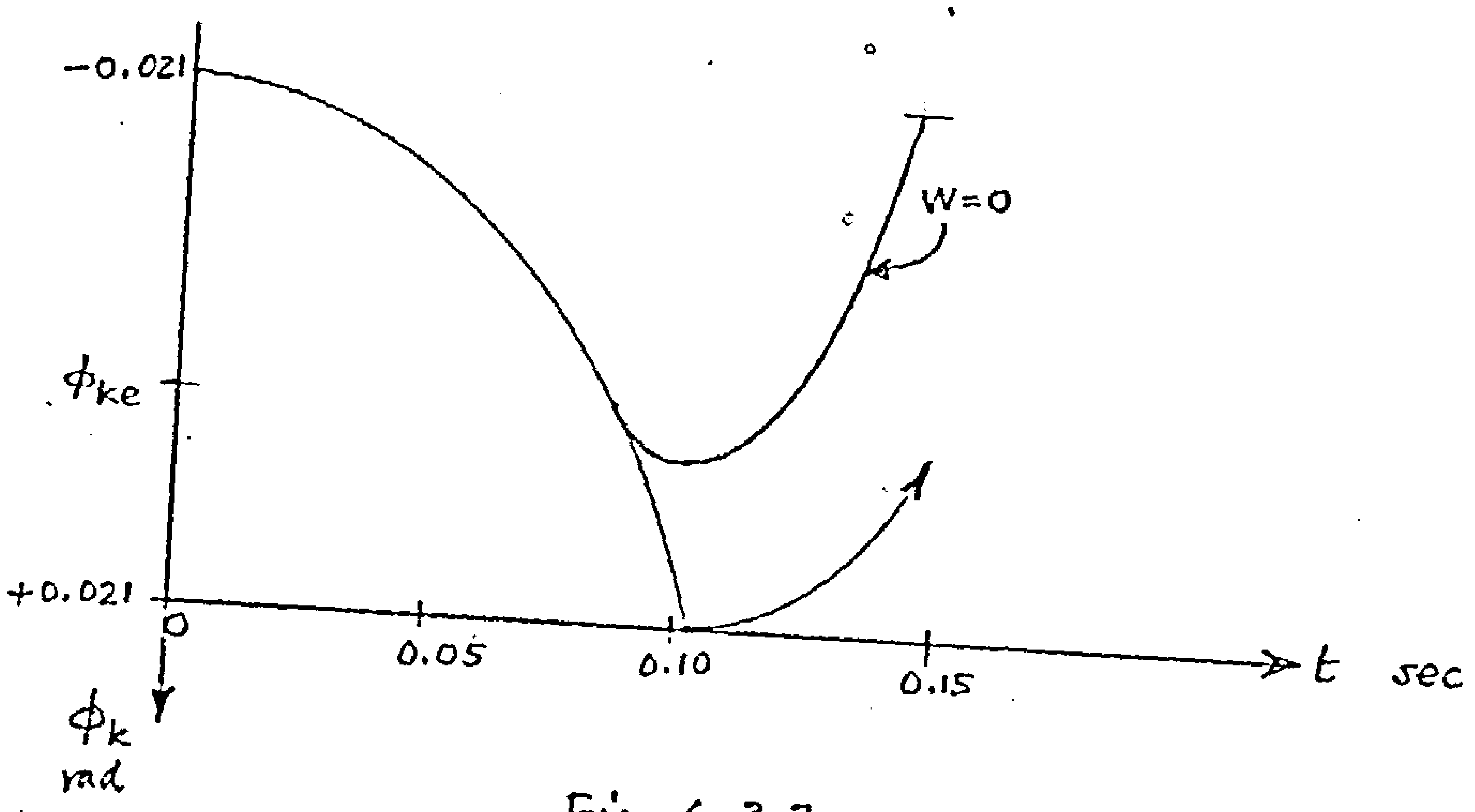


Fig. 6.3.2

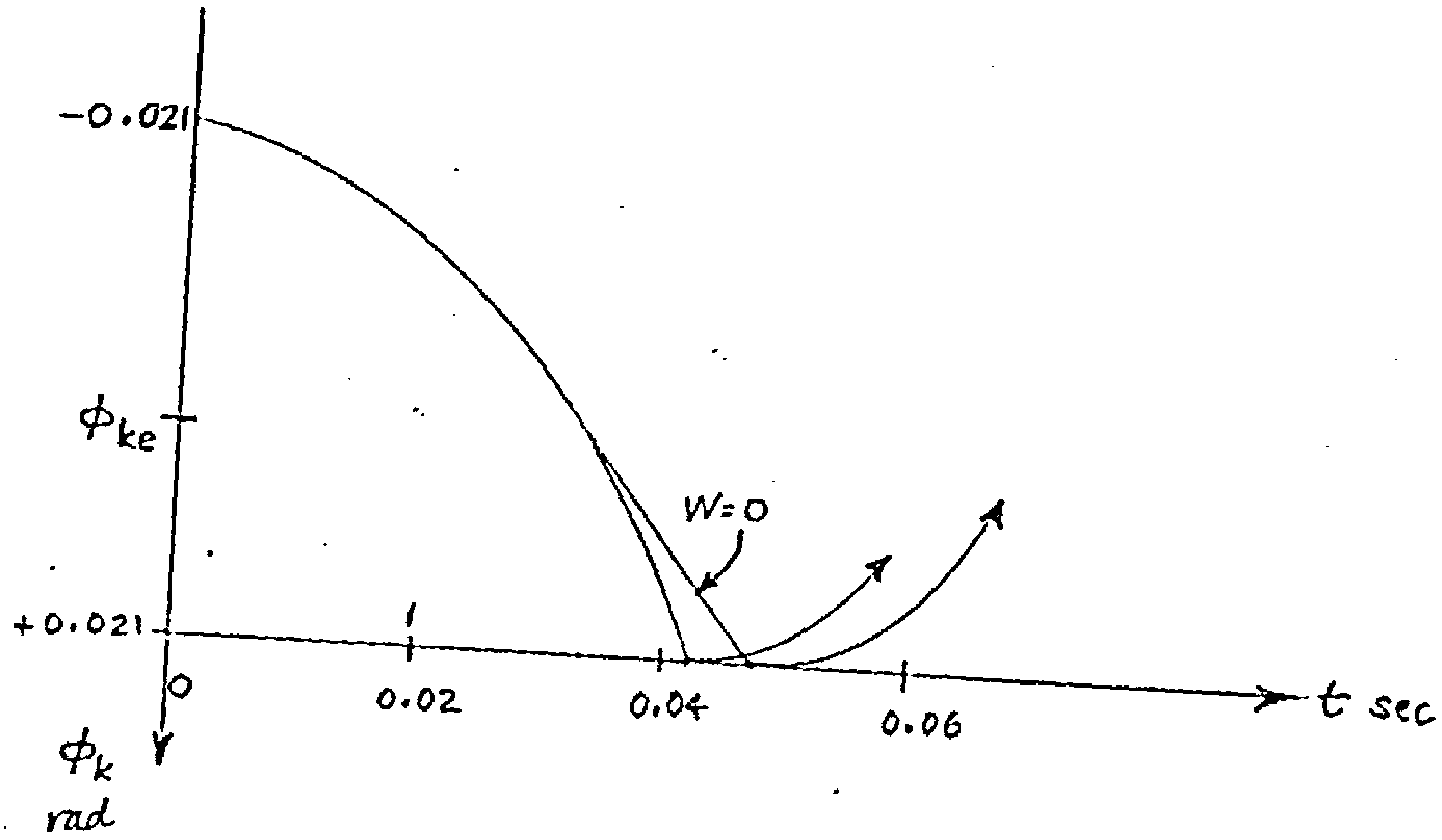


Fig. 6.3.3

to the key and then quitting it before it reaches the keybed. Now it is vitally important to realise that once the hammer has passed the point of escapement, its motion cannot be altered by the key. It follows that the amplitude of sound produced depends entirely on the velocity of the hammer at escapement, $\dot{\phi}_{he}$, and this in turn depends on $\dot{\phi}_{ke}$. In comparing the degree of staccato produced by different actions, we must obviously make sure that the amplitude is the same in each case. But this means that $\dot{\phi}_{ke}$ must be kept constant, and this places a severe restriction on methods of staccato production. As t_s occurs after t_e , it is useless to alter the function $\phi_k(t)$ before t_e because this function must always pass through ϕ_{ke} with the same gradient. It follows that it is pointless to use anything other than a normal finger action up to the point of escapement. However, after this point, one has the choice of withdrawing the finger or of pressing on to the bed. Let us simulate both cases (Program 6). Taking $W = 1.40$ N as far as the point of escapement (this gives a note of very low amplitude), and then letting $W = 0$ after this in one simulation, but not the other, gives the curves shown in Fig.6.3.2. We can see from this diagram that there is some advantage in withdrawing the applied force, as the key is then able to reverse more quickly and the total time taken is less. Now if we take, for example, $W = 2.94$ N (this gives a moderate amplitude according to the data of Ortmann and Ching) and repeat the procedure, the result is as shown in Fig.6.3.3. In this case the key has enough momentum to reach the keybed. As for the overall time taken, the situation is now reversed; withdrawing the applied force prolongs the reversal time. (The keybed has been assumed to give negligible rebound of the key; this is a fair approximation, but rebound is a factor which varies from piano to piano).

In assessing these simulations, one should not jump to conclusions. The model is not very accurate, and the differences in overall sounding time are very small - of the order of 0.01 sec. It is probably fair to say that in producing staccato it makes little difference how the key is depressed; the important point is to release the key smartly either during the descent, or as soon as it reaches the bed (this latter choice depending simply on one's usual method of depressing the key).

And now for a word on the vexed question of whether, as a general policy, one should strike the keybed with the key ("keybedding", as it is usually known). It is worth recognising from Fig.6.3.3 that even at a moderate tonal amplitude the key has so much momentum that it always reaches the keybed anyway - no matter what the finger does. Theorists please note.

6.4 TONE QUALITY

It is the aim of every pianist to draw a wide range of beautiful sounds from his instrument. As far as the playing of a single note is concerned, there are two variables: the tone quantity or amplitude, and the tone quality. The latter variable depends on the individual amplitudes of the various overtones which are present in a note. If several notes are played, then, of course, there are many other variables such as rhythm and relative amplitude, which can affect the resulting tone quality; however, we are concerned here with a single note, to be played without using the pedals.

Quantity is something which can easily be measured, but quality is more elusive. In his books, Ortmann describes the current (mid-1920's) state of opinion (other than his own) on the subject of tone quality. It was generally believed that many different qualities could be achieved independently of quantity. These qualities were measured on a subjective scale, but descriptions such as "sparkling", "velvety", "crisp", "pearly (jeu perle)", and so on were in wide, almost standard use. Breithaupt uses these sort of words with great exuberance, and describes different movements which, he says, will produce the different qualities. Fielden is more uneasy and distinguishes only between good and bad quality. Matthay places tone quality at the centre of all his work; his theory is that different types of accelerating key descent (more of these in Sec.7.2) give rise to different tone qualities. Indeed he goes further and describes which arm movements give these key descents. (The chief candidate for bad tone, in Matthay's view, is a motion which involves moving the elbow forward during the key descent; needless to say, Matthay does not produce a set of mathematical equations to support this intriguing theory).

Ortmann has done a thorough and valuable scientific observation (Vol.1 of his work) into the mechanical aspects of tone quality production. The chief points of his findings can be summarised as follows.

By studying a diagram of the action of a piano, we can see that the hammer always loses contact with the key before it strikes the string. Once contact is lost, the hammer embarks on a free flight. That is, the only forces acting on the hammer are:-

1. Air resistance.
2. Friction at the fulcrum.
3. Gravity.

Two conclusions may be drawn from this:-

1. The key no longer has any influence on the hammer.
2. $\dot{\phi}_{hs}$ depends only on $\dot{\phi}_{he}$ (for a given instrument).

This second conclusion assumes that air resistance and friction are in no way dependent on accelerations of the hammer previous to t_e.

Both quantity and quality must be determined by the dynamics of the hammer at the point of contact with the string. We can say that quantity is a function of $\dot{\phi}_{hs}$, $\ddot{\phi}_{hs}$ and all the higher derivatives. The same can be said for quality. Now it is obvious that the retarding forces listed above are always present in the same amounts. That is, the deceleration of the hammer due to gravity will always be 9.81 m/s^2, regardless of what the key or hammer are doing. Thus, the only possible variation in quantity and quality is caused by varying $\dot{\phi}_{hs}$ and hence $\dot{\phi}_{he}$.

As we saw in Sec.6.2 an increase in $\dot{\phi}_{hs}$ causes an increase in tone quantity (other things remaining constant). The theory of quality is not so simple, so let us say that it may or may not change as $\dot{\phi}_{hs}$ increases. Now we have seen that quantity and quality are single-valued functions of $\dot{\phi}_{hs}$, and in addition, that quantity is a monotonic increasing function of $\dot{\phi}_{hs}$. It follows that quality is a single-valued function of quantity, but the reverse is not necessarily true. Thus, we can make two deductions. Firstly, to change the quality, we must change the quantity. Secondly, it is useless to try to alter quality alone by altering the acceleration of the key.

This is the view held by Ortmann, Schultz, Ching, Harrison, Gat, and, more recently, by Taylor (1965). Fielden takes the opposite view, but does not press the point. Matthay is most vehement, and insists that anyone who cannot hear different qualities for the same amplitude is not listening hard enough. His reply to his critics is that:-

1. The key may rise in its bed during depression, thus accelerating the hammer all the way to the string.
2. "The string itself has some say in the matter".
3. Vibrations may be set up in the hammer shank which affect the vibrations of the string.

The first of these points is clearly incorrect, as we have seen that the point of hammer release is determined by the angle of the hammer, not the key. The second point cannot be defended, as the string is stationary until it is hit. The third point, however, has some degree of validity. In the previous argument, the hammer was considered rigid, whereas in fact, a certain amount of elasticity must be present. Hence, it is conceivable that different accelerations, previous to t_e, produce different vibrations and that these in turn produce sounds of different quality. However, there is no end to this kind of argument. One might also argue that the breathing of the pianist affects the viscosity of the air through which the hammer flies, and so on. The crux of the matter is surely:-

1. Is any modification of sound at all discernible, bearing in mind the limitations of the ear, discussed in Chap.1 ?

2. If there is any discernible modification, is it possible to have any <u>consistent</u> control over it?

So far we have been working from the basic definition of tone quality: that quality depends on the proportions of overtones present in the sound wave produced by the piano. Now, because musicians were very unwilling to abandon their notions of quality, a totally new concept was put forward by Ortmann, which is that it is the noise element at the beginning of the sound wave that is responsible for different tone qualities. The noise element is caused by the movement of the mechanism, the impact of the hammer on the strings, and the contact between finger and key. This theory was supported by Ching in 1934, but by 1946 Ching has changed his tune and rejects the whole idea. This refutation is based on a private correspondence between Ching and Sir James Jeans who believed that the noise element was negligible; most unfortunately, Ching does not give details of the correspondence. The noise theory is accepted by Schultz and Gat, and has attracted several recent writers, including Baron (1958) who supports it.

Considering first the noise produced by the mechanism and the hammer, it is obvious that this noise cannot be controlled by the pianist; indeed, it is dependent on the tone quantity.

which takes us back to the previous discussion of tone quality. Those people who argue that quality can be controlled in this way because a piano mechanism, when isolated from the strings, produces considerable noise when played are being irrelevant. However, the noise produced by the fingers can be controlled by the pianist, and needs careful consideration. Gat, having reluctantly accepted the idea that the quality of sound from the vibrating string is independent of quantity, seizes upon this type of noise and gives it great prominence in his work. He divides this noise into two categories: "upper" noise, produced by the impact of the fingers with the keys, and "lower" noise, produced by the impact of the key with the keybed. Armed with these variables, he discusses all manner of variation in tone quality supposedly produced by them. Now there can be no denying that this noise can be altered by using different finger actions, and hence here is a way of controlling quality. But the heart of the matter is: Is the change in effect noticeable, or is it totally negligible? Some writers attempt to prove their case by arguing that if the keys are slapped, considerable noise results; this ignores the fact that pianists usually depress keys in order to strike the strings. What seems to be overlooked is that the familiar signal-to-noise ratio operates here. A loud tone may have plenty of finger impact, but the noise produced would be almost entirely drowned by the sound coming from the sounding board. Conversely, a soft tone has very little impact. Moreover, psychological aspects must not be overlooked. Everyone knows that the sound of a ticking clock is soon eliminated from the conscious mind; no doubt the patter of fingertips would suffer a similar fate.

Still, it may be that this type of noise produces unwelcome sound. All that can be said here is that, as it happens, no good reason for striking the keys (i.e. using an impact at the surface) can be found in this thesis; and as for "lower" noise, there are so many advantages to be had from striking the keybed (as will be seen) that, rather than abandon this action, it would be more profitable to set to work to design a new type of keybed guaranteed to give a negligible bump.

So much for the undesirable properties of noise. What is remarkable about Gat's theories is that he believes noise to have desirable properties - adding spice to the sound, as it were. If this is so, then why does he not carry things further? How about clicking the tongue in Mozart's Turkish Rondo, or kicking the piano in time to Chopin's Funeral March? These sounds would be much more interesting than a rather insipid rattle of the fingers. Why pick on the fingers of all things? They have enough to do without having to produce special impacts as well.

When all is said and done, noise is noise after all. If pianists want to produce it or avoid it, that is their business; but whether their audience notices the difference is another matter. What has been shown in this section is that, noise apart, by simple objective reasoning we can see quite clearly that tone quantity and quality, as produced by the piano, are, to all intents and purposes, mutually dependent.

The only snag is that the brain is not an objective instrument. It is subjective. In fact, as far as scientific instruments are concerned, the pitch of a note is something which varies continuously through its spectrum; the brain, however, as we saw in Sec.1.10, takes a totally different view of things. If Whipple's theories are true, then there is the same sort of disparity between subjectively and objectively assessed amplitude; and amplitude, or tone quantity, is the variable we have just been using. Perhaps we should return to the discussion of tone quality and think more carefully.

Tone "quality" is the assessment by the brain of a particular mixture of overtones in the sound wave produced by the piano. So how does the brain make this assessment? Does it set up for itself a continuous spectrum of quality? It certainly does not do this for pitch, and most probably not for amplitude either. It does not seem entirely unreasonable to suggest that it is possible that the brain assesses quality in the same way as pitch and amplitude, by setting up a series of domains. Suppose we draw a hypothetical graph of quantity versus quality as an objective instrument might record it (Fig.6.4.1). It will be noticed that this graph is a straight line; this is quite easily arranged by distorting the scales of the axes. (See footnote). Quantity is subjected to the usual logarithmic distortion. As for quality, nobody knows how that should be distorted - but this does not destroy the argument. Now suppose we draw a "graph" of what the brain would hear under the hypothesis of a domain assessment of quality. Quantity is now divided into seven regions, as suggested by Whipple, and the widths of the regions are made equal, which is reasonable considering that amplitude follows the Weber-Fechner law and the scale of the axis is logarithmic. How quality should be divided is not even

Footnote: This could not be done if a given quality occurred at two different levels of quantity, but such an occurrence is no more than an academic possibility.

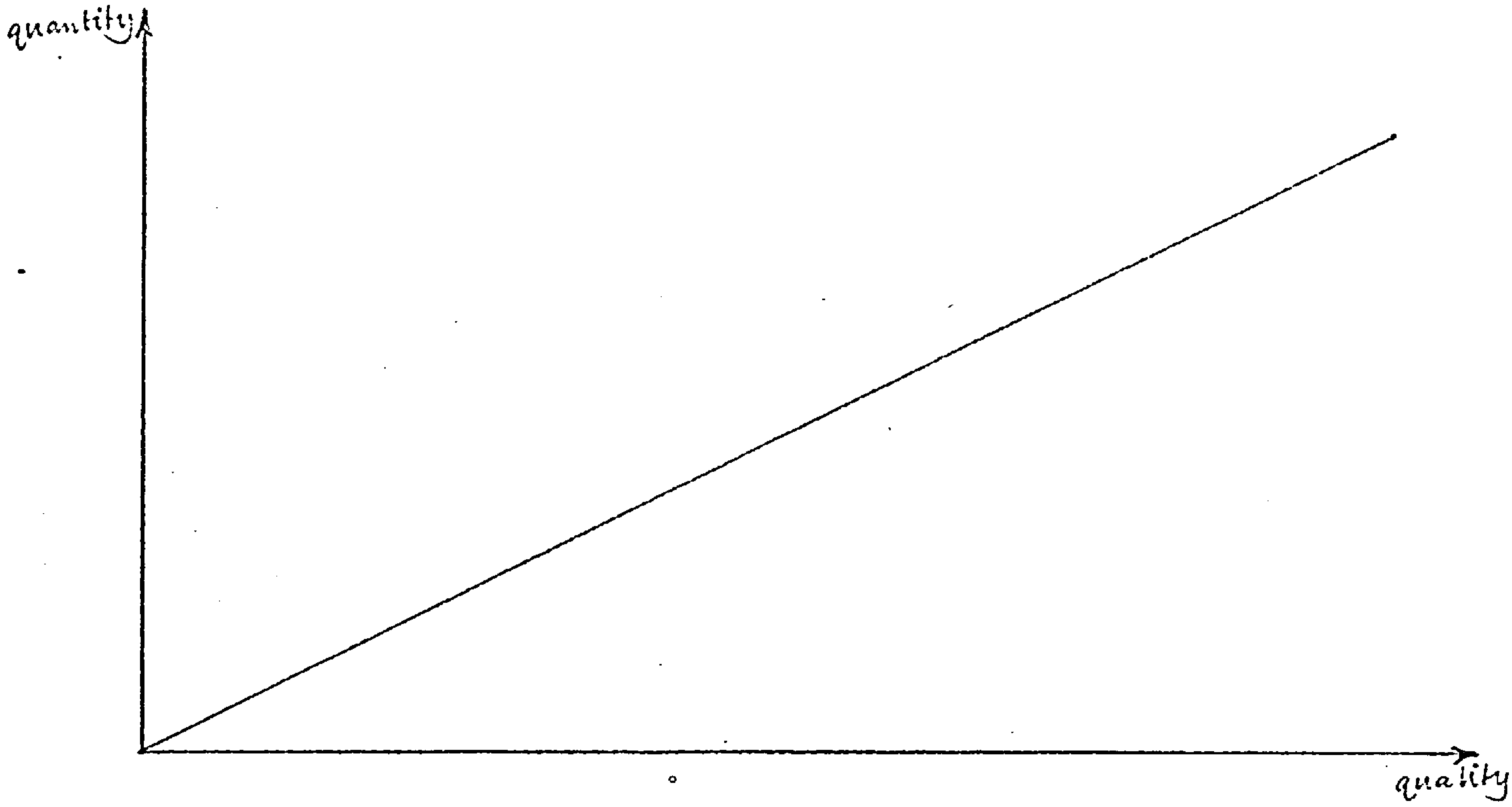


Fig. 6.4.1 Objective hearing.

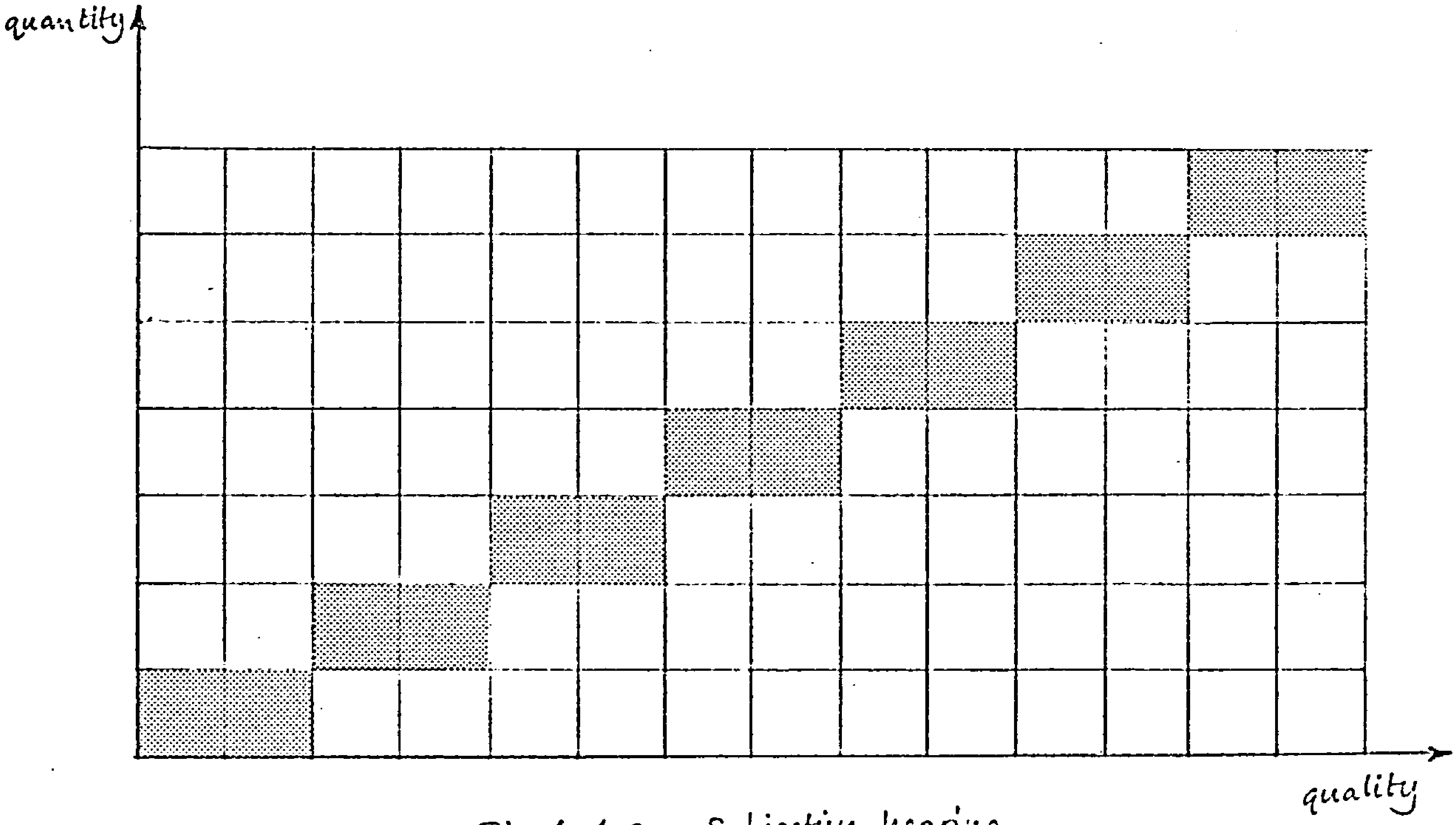


Fig. 6.4.2. Subjective hearing.

debatable, but, as Ortmann gives quite a long list of different qualities, suppose for the sake of argument we divide the quality scale into 14 equal regions (Fig.6.4.2). Now the ear will no doubt follow the objective graph of Fig.6.4.1, but the brain will presumably match one domain against another. This action is shown as the shaded area of Fig.6.4.2. What is immediately apparent is that for each domain of quantity, there are two corresponding domains of quality; or to speak in practical terms, it is quite possible, under our hypothesis, for a given level of amplitude, say "mezzo-forte", to permit the production of two different types of tone-quality, perhaps "velvety", and, who knows?, "pearly".

Now the hypothesis on which this argument is based is that quality is assessed as a series of quite distinct domains - perhaps a rather far-fetched idea. And yet consider that, for the piano, all members of the western world, except the most unmusical, mentally divide its range of pitch, from bottom A to top C, into 87 equal parts - not 86, that is, nor 88, but exactly 87. The idea that the preliminary stage of musical appreciation consists of the recognition by the brain of different domains organised within its own cells should not be dismissed lightly. And certainly, those scientists who in the past have assured overimaginative musicians that they have been hearing things ought to be reminded that when they look at their measuring instruments, they are consulting the wrong devices. They ought to be consulting the brains of the musicians.

Well, all this is just theory-spinning; a hypothesis is only a hypothesis after all. But the damage has been done. The hypothesis cannot at the moment be disproved, and, until it is, pianists can no longer be sure that their quality depends entirely on their quantity.

7

THE COMBINED ARM/KEY SYSTEM

7.0 INTRODUCTION

So far we have modelled the arm by itself and the key mechanism by itself. Now for the difficult part: putting the two models together. This should give something like a realistic representation of actual piano playing. We have seen that up-and-down oscillation of the arm through a 1 cm. displacement is limited in speed to about 8 Hz. due to the mechanical properties of the arm, and it is only to be expected that a finger is similarly limited. We saw in Chap.1 that a pianist is often expected to play a sequence of notes at a much faster rate than 8 per second. Clearly such a passage cannot be played entirely by a set of arm actions and therefore finger actions must be used in some way; the obvious advantage of using the fingers is that, as there are five (including the thumb) on each arm, they can share the job of up-and-down movement. This leads one to ask if there is any point in using anything but finger actions; the answer to this is that fingers simply do not have enough strength to play many passages. (Although a finger may appear to be quite strong, it may not have much <u>available</u> strength in piano playing; this is discussed at length in Chaps. 9 and 10).

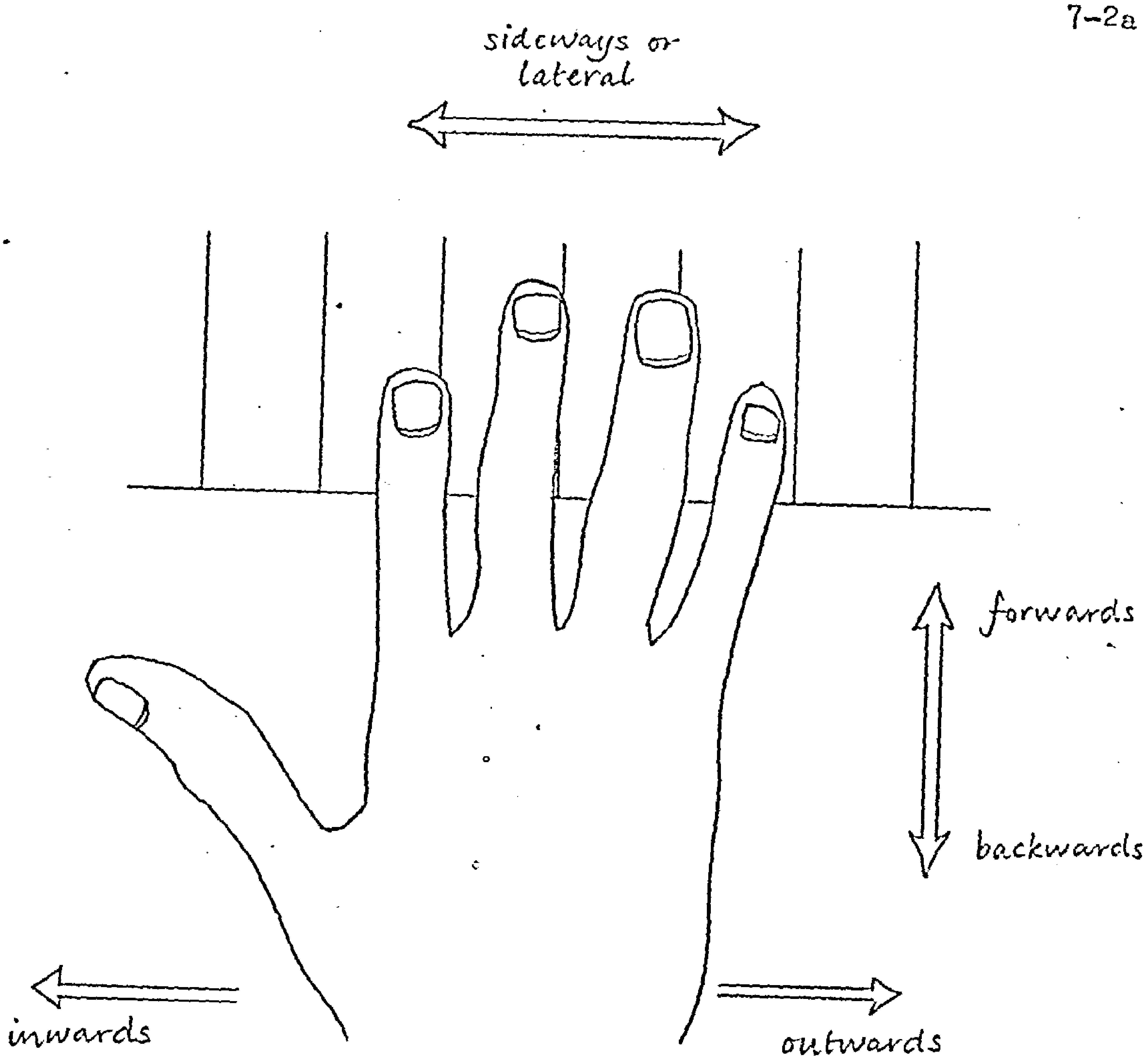
Thus we can draw a reasonably clear distinction between a passage played by an arm action, where the fingers are held firmly but play a passive role, and a passage played by finger action, (usually called a "finger passage") where the arm is relatively unmoving and acts as a base for the fingers. Ching makes such a distinction and says that, very approximately, an arm action is used for half of all notes played. This seems reasonable enough.

In this chapter, arm actions will be discussed, together with some general physiological problems. A full discussion of finger actions will be left until Chap.9. First of all, however, we need to define terms. Fig.7.0.1 shows a hand and a keyboard, with some basic directions indicated.

7.1 SIMPLE DEPRESSION OF THE KEY

In the last chapter, we took the force applied to the key, W, as being constant throughout the descent, (sometimes abruptly switching it off at the point of escapement). Knowing what we do about the properties of the arm, it is clear that the arm is unlikely to be able to depress the key with a force which is constant.

Suppose we consider the act of playing a single note by means of an arm action. For the moment, assume that the wrist and hand are kept rigid, and that the arm is rotated downwards about the elbow. A note of moderate amplitude can quite easily be produced by starting this movement at the key surface and taking the key down to the point of escapement, or further. However, suppose it is desired to play a note loudly. In view of the descent time given by Ching (Sec.6.1.1: Ching gives a



NB Inwards and outwards reversed for left hand

Fig. 7.0.1

figure of 1/150 sec. for a very loud note) and the curves of the build-up of muscular tension (Sec.3.3.1), it is not at all clear whether the arm is capable of producing such a rapid movement if it starts only from the key-surface; in fact, we may be forced to start the arm some distance from the key-surface and attack the key with an impact.

Let us see what can be deduced from a simulation. We can have some degree of confidence in our modelling as the movement under discussion is simple and one-directional. Modifying equ. 4.4.2 to

$$p_1 F_1(t) \sin \psi_1(t) - p_2 F_2(t) \sin \psi_2(t) + l W(t) = I \ddot{\theta}(t) \qquad (7.1.1)$$

keeping equs.4.4.1, 4.4.3, 4.4.4, 4.4.5, and equs.6.1.1 to 6.1.6 intact, adding the relation

$$-l\ddot{\theta} = x_f \ddot{\phi}_k \qquad (7.1.2)$$

(which makes the usual small angle approximation) and adding the condition that $\theta = 0$ when the arm touches the key surface, gives a complete model of the arm/key system. Equs.7.1.1, 7.1.2, and 6.1.2 can be combined to give

$$p_1 F_1(t) \sin \psi_1(t) - p_2 F_2(t) \sin \psi_2(t) = -I_c \ddot{\phi}_k - \rho c_p g \qquad (7.1.3)$$

where $I_c = I/\rho + \rho I_p$, $\rho = l/x_f$

This applies to phase 1; phase 2 can be represented by changing I_p to I_p' and c_p to c_p'.

Now if the key is to be depressed, with the fingertips starting at the key surface and the elbow muscles working at maximum stimulation, then $\zeta_1(t) = 0$, $\zeta_2(t) = 1$, $\theta(0) = \dot{\theta}(0) = \dot{\phi}_k(0) = 0$ and $\phi_k(0) = \phi_{k0}$. A simulation of this model (Program 7) gives the result shown in Fig.7.1.1. The total time of key descent is 0.026 sec. Now Ching's time of 1/150 sec. is very much shorter than this. The only way in

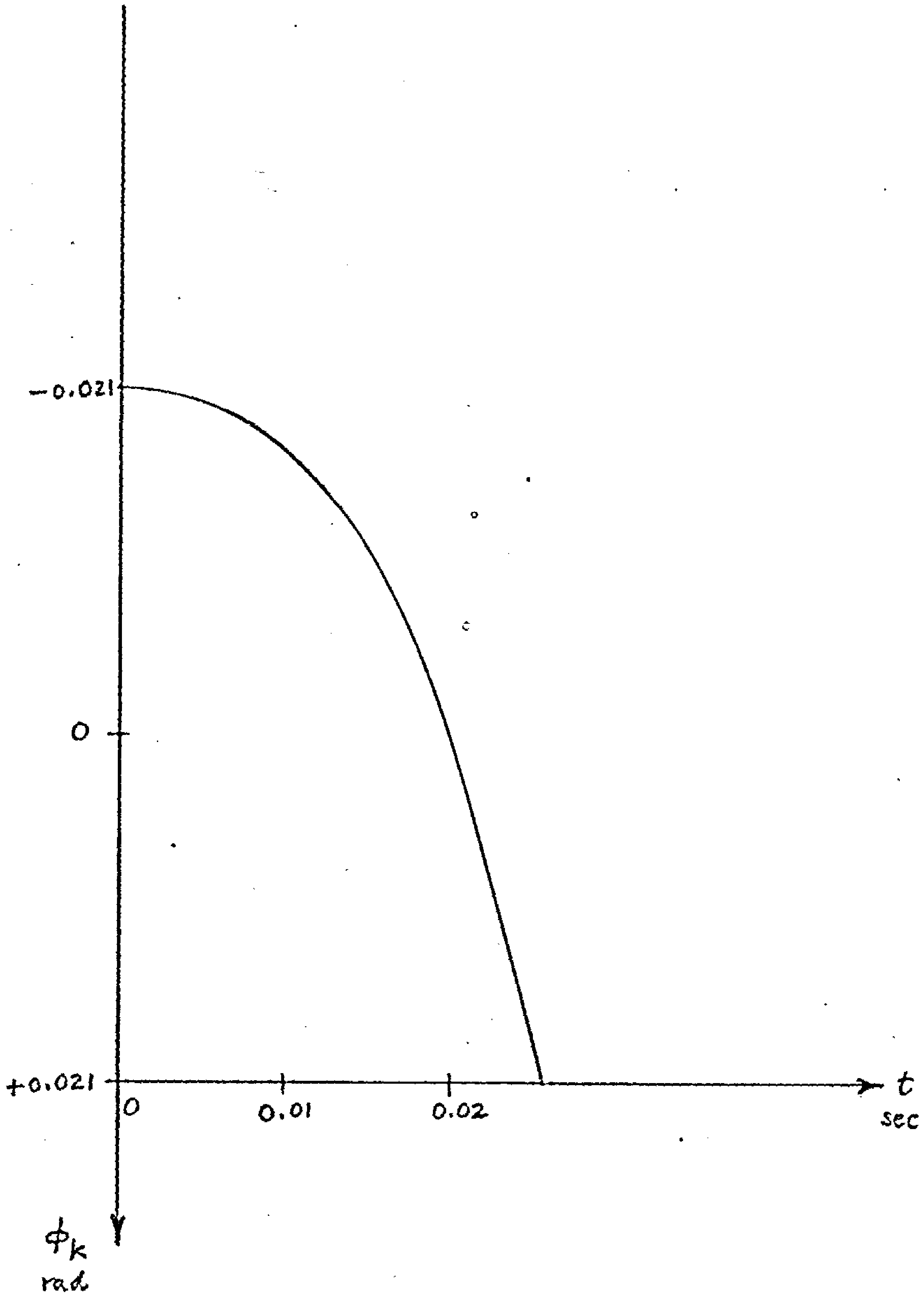


Fig. 7.1.1

which the descent time can be shortened, as far as our model is concerned, is by using an impact start. The effectiveness of such an action stems from the fact that the initial acceleration of the arm, which consumes most of the descent time, takes place away from the key.

In discussing impact the first thing to be decided is the degree of elasticity at the moment of contact, i.e. the value of the coefficient of restitution. Schultz is the only writer to worry about this; he describes the finger as being an "imperfectly elastic body" and the piano key as "virtually, of course, a perfectly elastic body", and goes on to deduce that the impact is elastic. But it seems to me that the piano key is not particularly elastic and that the finger is almost totally inelastic; in this case the collision between them should be almost perfectly inelastic. This point can easily be tested by dropping a wooden slide rule with a plastic surface (which is almost identical in composition to a piano key) on to the upturned fingers; there is virtually no trace of a rebound.

Having made his decision that the key bounces away from the finger on impact, Schultz places this theory at the centre of his work. His ideal in key depression is what he calls a "controlled key descent" which, amongst other things, must start with no bounce and hence, by his theory, with no impact.

It would probably be near the truth to model an impact as follows: part 1 of the arm stroke uses equations similar to those in Chap.4; part 2 of the stroke uses the equations of this section; the boundary condition between the two parts is that at the moment of collision the key is given, instantaneously, a velocity the same as that of the finger. (To be more precise: if we use the principles of impulsive motion (Goodman and Warner, 1963) we obtain the relation

$$\frac{x_f}{l} = \frac{I_p \dot{\phi}_k'}{I(\dot{\theta}' - \dot{\theta})} \qquad (7.1.4)$$

where the dash indicates a variable just after collision. Using equ. 7.1.2 gives

$$\dot{\theta}' = \frac{I}{I + \rho^2 I_p} \dot{\theta} = 0.67\,\dot{\theta} \qquad (7.1.5)$$

using our standard data).

But despite this discussion, some doubt must be cast on Ching's data. 1/150 sec. is a very short space of time indeed. It seems to me, from my own experiments on a piano key, that a key does not need to descend anything like so fast to produce a very loud note - indeed, a descent time of the order of 1/30 sec. appears to be short enough. Actually, it seems that Ching has copied his figure from Ortmann, who gives an identical time. One wonders how Ortmann can say categorically that 1/150 sec. produces the loudest tone. Why stop there? There is no real limit to the rate at which a key can be accelerated downwards, and the resulting tonal amplitude will increase indefinitely. One has visions of Ortmann happily wielding a sledge-hammer; certainly it is not without significance that he conducts his experiments on a special isolated key mechanism provided by a firm of piano makers.

To sum up: we have shown from a simulation that the arm, rotating about the elbow with a stiff wrist, can depress a key with a descent time as short as 0.026 sec., which in my opinion is ample for the production of fortissimo.

So far we have discussed the playing of one key. If a chord is played, then equ.7.1.1 must be modified to

$$p_1 F_1(t) \sin\psi_1(t) - p_2 F_2(t) \sin\psi_2(t) + nW(t)\ell = I\ddot{\theta}(t) \qquad (7.1.6)$$

where n is the number of keys depressed. Clearly, the more keys depressed, the more the arm is slowed down, and it may become necessary to use an impact - at least when using a simple rotation at the elbow with a stiff wrist. However, when just one chord is struck, it seems possible that the hand can be coordinated with the arm to produce a double-linked movement with the forearm rotating about the elbow and the hand rotating about the wrist to give a whiplash effect. This would probably be enough to play a loud chord starting from the key surface.

7.2 THE EXTENT OF KEY DEPRESSION

In Chap.2 we saw that one very controversial topic was whether the key should be taken down to the keybed or released somewhere around the point of escapement. Let us now examine this question.

Let us consider first the case where a sequence of movements has to be made as fast as possible, with quality of performance of secondary importance. Then, on the face of it, time is saved by reversing the movement of the arm or finger as soon as possible; whether this is practicable or not will be discussed in due course. However, suppose we are concerned with a set of movements made at submaximal speed; then we have a clear choice as to whether to "keybed" or not.

We saw in Sec.6.3 that, as often as not, a key will have so much momentum at the point of escapement that it will carry on to the bed whether the finger is released or not (many writers do not recognise this); therefore we should define "keybedding" as being when the finger, as well as the key, is taken down to the bed. In Sec.6.4 it was explained that there may be an undesirable amount of noise generated by an impact at the bed, which provides one reason for <u>not</u> keybedding. Ching, who disregards this effect, states that keybedding is very desirable because it enables movements to be standardised (the advantages of standardisation are discussed in the next chapter). Ching's reasoning is that if one attempts to stop the descent of the finger at a predetermined level, then it is very difficult to judge this level with any degree of accuracy and hence there will be an increased tendency for amplitude levels to be imperfectly controlled. This theory is perfectly true if, for example, the finger descends for only a quarter of the total key-depression depth, because then the pianist has to judge not only the magnitude of the force to be applied, but also the extent of application of this force, and therefore there is double opportunity for error. Once the point of escapement has been passed, it no longer matters what happens to the finger or the key, and in this region no error can occur through misjudgment of the depth of key depression. However, it is very much more convenient to carry the finger on to the keybed, because one can then be careless about the following upward movement of the finger (unless an extreme staccato is desired). The virtues of convenience will be expounded in the next chapter.

These remarks apply to arm passages. For finger passages, there are further advantages of keybedding; these are explained in Chap.9.

Closely related to the question of keybedding is the notion of a "controlled key descent". Schultz starts his book by defining what he means by such a descent. Firstly, there should be no impact, as already mentioned. Secondly, the finger must be in contact with the key throughout its descent (Schultz advocates keybedding). The reason for this is that "the finger has more time in which to plan its descent". Schultz does not explain what he means by this impressive phrase. He does say, however, that there is a great likelihood of the finger losing contact with the key, but as we saw in the last section this is a somewhat exaggerated fear.

Matthay has rather similar views to Schultz: there should be no impact, and the finger should "feel the key" down to the "moment of tone-production", wherever that is. Matthay has the fantastic notion that a finger should move the key downwards with an increasing acceleration (presumably the third derivative of position is constant), and that this motion can be continuously altered actually during the key descent by means of the finger sensing the resistance of the key. Truly, Matthay expects miracles of the finger.

These ideas of controlling the key through its descent seem misguided. The descent must surely be too fast for any conscious control. It follows that the important factor is the choice of nervous signals sent to the arm muscles atthe start of the movement. What the key does after this cannot be helped. Control can only come from standardising these input signals as the result of experience. This is the view taken by Ching.

7.3 REVERSAL OF MOVEMENT

We saw in the last chapter that staccato playing by means of an arm action demands that the arm rapidly reverse its motion at the end of the key descent. Similarly, any passage which is to be played by a series of rapid arm movements incurs this problem of rapid reversal. As discussed in Sec.4.0, the reaction time of voluntary movements is always greater than about 0.2 sec., and so all rapid reversals must be controlled by preset mechanisms. It is not obvious how this control might be achieved. Several possibilities come to mind.

One possibility is that the input signals to the muscles are sent out consciously (or perhaps one should say semi-consciously) as follows. A signal is sent out to the muscles which lower the arm, telling them to operate immediately. Simultaneously, a signal is sent out to the raising muscles, ordering them to operate after a specified delay. This is control by timing.

A second possibility is that of control by position. Because of the high speeds involved, the ordinary position-sensitive feedback is no use, but perhaps instead some sort of triggering arrangement occurs. It may be that the ordinary position-sensitive devices can be preset to trigger a new input signal to a muscle. For example, when the piano key is about to be depressed, it may be possible to set the control system of the arm muscles to reverse when its displacement reaches 1 cm.; that is, the signal to the downward muscle is to switch over to a signal to the upward muscle at this displacement.

A third possibility is that of control by force. The force-sensitive receptors in the muscle may be able to trigger a new input signal in the same way as before when a sudden increase in force occurs, for example when the keybed is struck. (This of course would only apply if one had decided on a policy of keybedding).

If these ideas of triggering seem farfetched, perhaps the so-called "Golgi tendon organs" (Milsum, 1966) should be mentioned. These are devices which occur in tendons and whose purpose is to detect a sudden force (they are rather similar to the positioning devices in the muscles, but instead of showing a linear response, they have a step-function output which is only given if the force input has exceeded a certain high threshold level). To give an instance of the way they work: if one stumbles, the muscles round the ankle receive a violent stretching force. Now if a fully stimulated muscle is stretched too quickly, it will rupture (Young and Stark,1965) Because of this danger, the Golgi organs in the ankle tendons immediately instruct the ankle muscles to relax. Admittedly the ankle then "turns over" and is strained, but this is presumably less catastrophic than a torn muscle.

Three ideas have been put forward here - control by time, position and force. Presumably, at least one of these theories is somewhere near the truth, because rapid reversals certainly can be achieved. Perhaps indeed muscles are controlled by all three mechanisms. It goes without saying that, in order to produce a definitive study of piano technique, one has to discover just what switching mechanisms exist. However, that lies beyond the scope of this thesis.

7.4 THE PLAYING OF ARM PASSAGES

So far we have studied the playing of a single note or chord by means of an arm action. Let us now look at the playing of a series of notes or chords by arm actions. The chief factor in such a passage is the mechanical limitation of the arm when oscillating, as discussed in Chap.4. We can assume that for a very fast passage, a great deal of strength is needed. It was mentioned in Chap.4 that Schultz disagrees with his colleagues and reaches the conclusion, on intellectual grounds, that not much force is needed to play a rapid arm passage. We need not tarry over his analysis, but it is worth noting that he concludes it by writing

> "if strength were a direct determinant of velocity, the pianist who pounds his instrument for six hours a day in a commercial orchestra would be able to exceed the facility of certain of our women pianists who, although definitely not the possessors of prodigious strength, are yet capable of unsurpassed velocity".

One can sympathise with Schultz's horror of the displacement of the Euterpean by the Mammonish, but the theories of his fellow writers seem more convincing.

An important factor which has led to much dubious theorising in the literature is that of the relative inertia of the links that make up the arm. Most of the authors we are considering assume unquestioningly that, the larger a link is, the slower must its maximum speed be; the implication being that as the speed of a passage increases, the load of key depression must be assigned to smaller and smaller links. Thus the most rapid octave passages, according to many writers, can be achieved only by using an oscillation of the hand from the wrist, the rest of the arm being held stationary. Indeed, Schultz, having explained this at some length, feels it necessary to apologise for having laboured over such an obvious point.

Now, in fact, a dimensional analysis lies at the heart of any investigation into relative inertias. For example, if two links are identical in shape and musculature but vary in size by a constant scaling factor, then the ratio of their lengths is that of the scaling factor, the ratio of their muscular strengths is that of the square of the scaling factor (muscular strength depends on the cross-sectional area of the muscle), and the ratio of their moments of inertia is that of the fifth power of the scaling factor. In the arm, the links are in proportion with each other in that the shoulder has powerful muscles to operate the whole arm and the fingers, being much smaller, have only small muscles. A dimensional analysis to study the relative behaviour of each link in the arm would be most interesting and useful, but such an investigation is not carried out here, because there is a great lack of data. Ching comes nearest to realising the essentials of the problem. He conducts an experiment, in conjunction with a scientist, into the maximum rates of oscillation which can be achieved by various parts of the body. The result of the investigation is that this maximum rate is virtually the same for all parts of the body. However, this experiment only takes us half way, because it is concerned with minimal movements (i.e. a series of very small taps) and so it is in essence a measurement of the capabilities of the nervous system. But the most important factor in any dimensional argument is that of the displacement of each link. Now for playing the piano the ultimate output displacement is that of the piano key, namely 1 cm (rather more if one uses an impact; rather less in the repetition mode). Speaking intuitively, it seems to me that the performance of the forearm oscillating at maximum speed about the elbow over a 1 cm end displacement is equivalent to that of the finger oscillating at maximum speed over something like ½ mm end displacement (which is less than the amount of "give" in the flesh of the fingertip). The implication of this is that in playing the piano, it is the forearm which is the fastest link, not the finger. To summarise: most writers say that in playing the piano the forearm is slower than a finger; Ching says it is as fast; I say it is faster. Similarly, one would expect the hand oscillating about the wrist (with the forearm stationary) giving a 1 cm displacement to have a maximum speed in between that of the forearm and the finger.

In view of what has been said, how should we tackle an arm passage, for example a series of octaves? The simplest movement is that of a rotation about the elbow with the wrist rigid and the fingers held firm, and this action has much to commend it.

Only simple muscle switching need be carried out, and so there are few problems of coordination. The moment of inertia of the forearm and hand can be slightly reduced by bending the hand downwards at the wrist (i.e. as a constant position); this also improves the structural strength of the fingers (see Chap.9).

As the inertial reaction of the key increases with tonal amplitude, the loading on the arm increases with amplitude and therefore it is reasonable to say that, under the condition of maximum effort, the frequency of a passage played by the action described be slightly reduced if its amplitude is increased. (Bear in mind that, at maximum effort, it may be necessary to dispense with keybedding). This can be described by a graph such as that of curve 1 of Fig.7.4.1 (which is hypothetical). In other words, there is a tradeoff between frequency and amplitude and the pianist must make his choice.

However, this curve is one representing maximum effort. Now we saw in Sec.3.4 that maximum effort is not something which can be sustained for any length of time, as Fig.3.4.1 shows, and, the longer the passage is, the more the muscular stimulation must be reduced. Therefore, curve 1 is the extreme member of a family of curves, typified by curve 2 on the same diagram, each curve representing the relationship between frequency and amplitude at a given degree of stimulation.

The action just described is not the only possible movement for an arm passage. Consider the following arrangement: The wrist is kept fairly relaxed, and the forearm is oscillated about the elbow, but with a very small displacement - say about 3 mm at the wrist (Fig.7.4.2). The forces F_3 and F_4 are provided by the muscles lying in the forearm which control the turning of

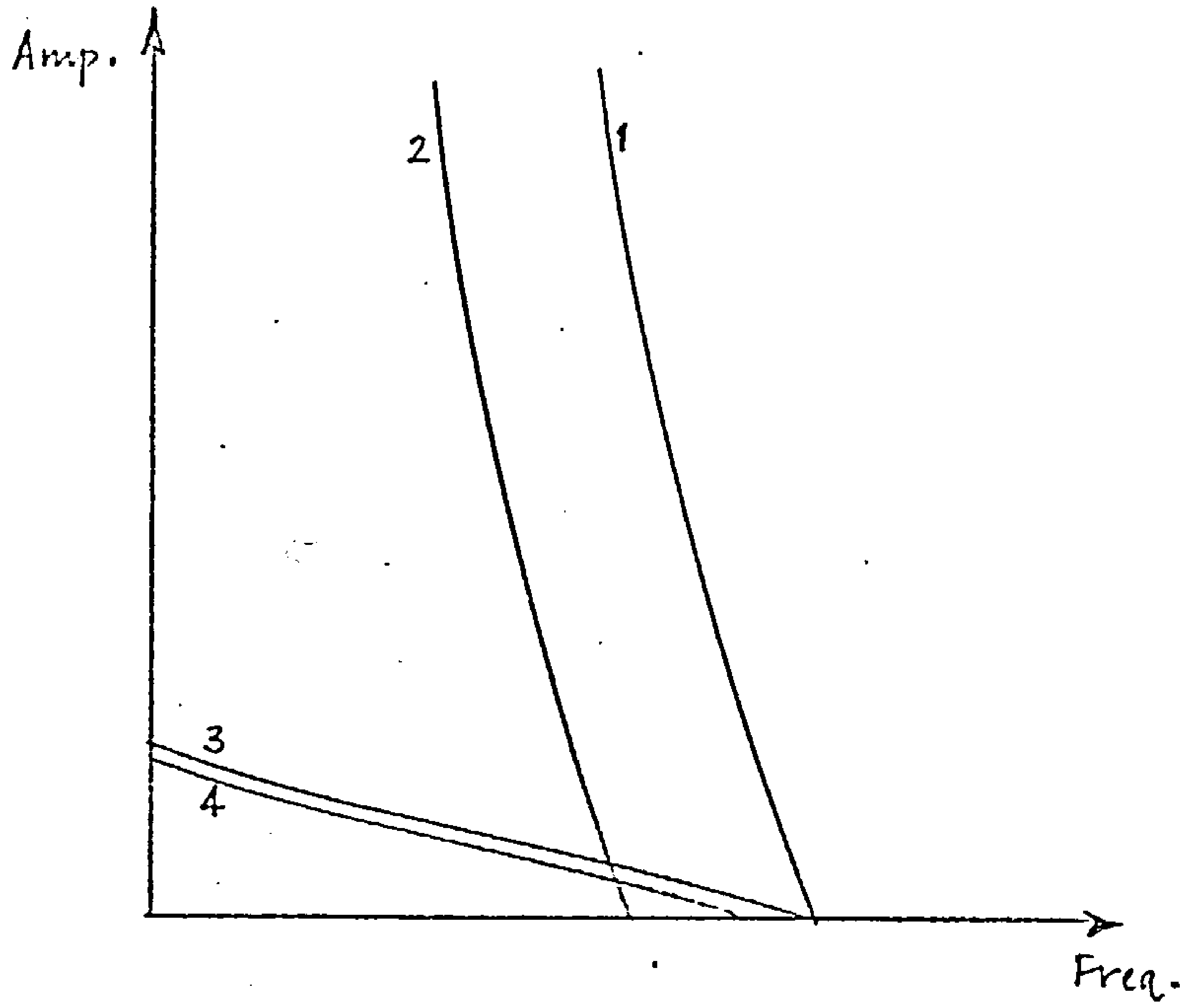


Fig. 7.4.1

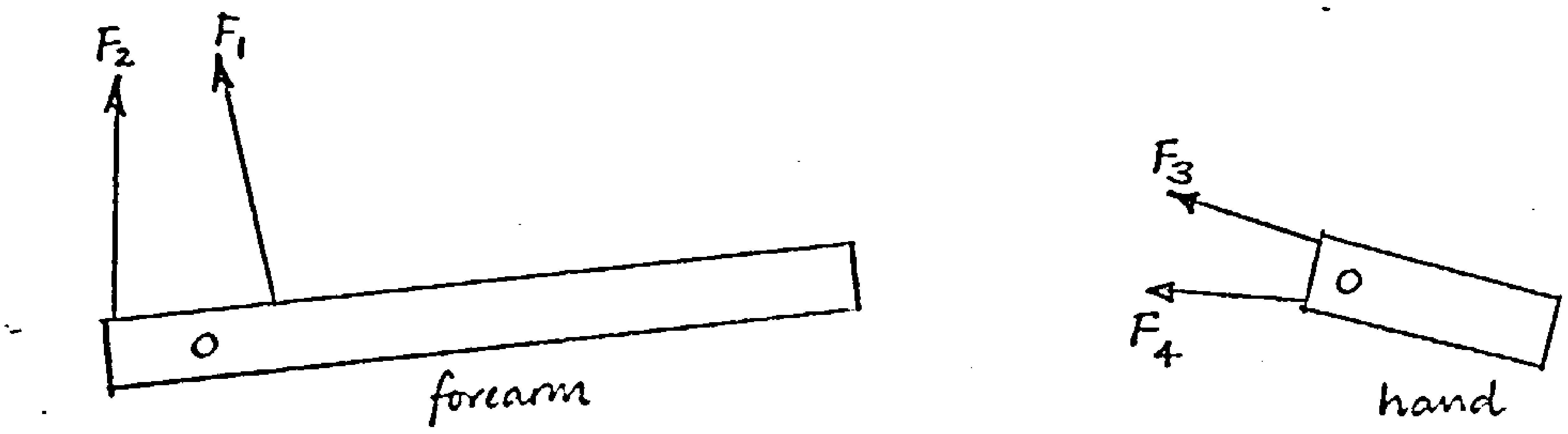


Fig. 7.4.2

the hand. Simple experiment shows that the force outputs of these two sets of muscles can be adjusted each to a <u>constant</u> level so that the hand oscillates at the same rate as the forearm, but at the same time turning back and forth about the wrist relative to the forearm (i.e. something of a controlled shake). The forces F_3 and F_4 clearly provide a restoring torque, not by virtue of their F^M components, but by some passive mechanical components: whether K or $\zeta\mu$ of our muscle model, or whether another component such as the restraining tissue at the wrist is difficult to say. (I would guess the latter).

Now this action is one in which the hand acts in a passive way effectively as an amplifier of the forearm oscillation. The advantage of such an action is that its performance characteristics may be more favourable in some respects than those of the previous action. As, in this new two-link movement, the forearm oscillates with less displacement than before, one might expect a greater resistance to fatigue. On the other hand, the lack of rigidity of the wrist puts passages of high amplitude out of bounds. The amplitude-frequency characteristics at maximum stimulation for this action could perhaps be described as shown in curve 3 of Fig.7.4.1. In this admittedly hypothetical diagram, curve 1 dominates curve 3 over all values of frequency. The pianist should obviously use whichever action has the dominating curve at the frequency and amplitude at which he chooses to play, and, faced with two curves such as these he should choose the method of curve 1 at all times. However, we have been considering maximum stimulation. Suppose we now consider the playing of a lengthy passage which can be achieved only by reducing the stimulation level of the elbow muscles to, say, 60%. We can take curve 2 to represent this level for the one-link oscillation and we can add curve 4 to the diagram, representing 60% stimulation in the two-link model. Curve 4 has been drawn relatively close to curve 3, reflecting the greater resistance to fatigue of the two-link action. We can see that, at high values of frequency and low values of amplitude, curve 4 dominates curve 2 and, still pretending that the diagram is true, we can say that the two-link action should be used by the pianist if he is playing a lengthy passage in this range. Unfortunately, no data can be given here to back this discussion, but it is hoped that it has been made clear how a proper analysis of arm passages should be carried out.

We have only touched on some basic aspects of arm passages here, and the subject is very complicated. Performance of an arm passage is greatly affected by whether the mode of each key is normal or repetitive, and again by whether the transition from one key to the next is made between white keys, between black keys, or from one to the other; in this latter case, the oscillation must be larger and hence frequency is reduced. In addition, the spacing between each chord or pair of notes in an arm passage has an enormous influence on the speed at which the passage can be played.

Further topics are (1) the amount of key depression and (2) whether to play towards the front or the back of the key. Possibly energy methods might be used as a method of analysis, but the solution is by no means simple.

7.5 SUMMARY

In Chap.2, a brief review of arm passages (in the form of octaves) was given. Clearly, writers are unwilling to dispense with the services of the upper arm for playing octaves. Most writers state that the upper arm should take part in the upward and downward action. Ching however thinks that upward and downward action should be confined to the forearm, and says that pianists should therefore sit nearer to the piano so that the elbow makes an angle of about 90 degrees. Having said this, though, he goes on to say that the upper arm should swing backwards and forwards in synchronisation with the forearm.

Ching is probably right in wanting only the forearm to give vertical oscillation; the forearm is, most likely, just as fast as the upper arm. But why does he use the upper arm at all? Such a combined motion as his only introduces difficulties in coordination. It seems to me that in arm passages the upper arm can make no positive contribution save that of moving the elbow sideways to position the forearm.

8

OPTIMUM MOVEMENTS — OR WORSE

8.0 THE CRITERION BEHIND PIANO TECHNIQUE

The last chapter contained a discussion on finding the most efficient movement of the arm for playing chords or octaves. But how should one define what is most efficient? Writers on piano playing have a habit of nodding their heads wisely and pronouncing their own techniques to be most excellent because in carrying them out "as little energy as possible is expended". This is a gross oversimplification of the problem. Certainly, minimisation of the total mechanical energy is no criterion, because as we saw in Sec.3.5, chemical energy expended is the real measure of work done. But even this is not an accurate indication. There is no point in sparing the elbow muscles if the fingers are thereby worked to a standstill. Fatigue is a far more relevant variable than chemical energy; and fatigue is a complex factor involving nervous effects and the straining of inelastic tissue, not to mention muscular effort. Obviously, if it is possible, fatigue should be spread throughout the arm to avoid one link of the limb being overloaded; in general, the big muscles of the arm can take much more punishment than the muscles of the fingers.

Even the minimisation of fatigue with all its aspects carefully balanced is not an ultimate criterion. There are occasions on which a pianist should abandon all thoughts of avoiding fatigue in order to produce the best interpretation of a passage. In fact the true criterion of piano playing, from a technical standpoint, is one which is built up from the performance specifications laid out in Sec.1.11, each variable being weighted according to the personal preference of the pianist. We saw in Chap.7 how two of these of these variables, frequency and amplitude, (other variables being constant) are in direct tradeoff, but perhaps the best example of tradeoff is between accuracy and a variable such as tempo. In this case it really all depends on the temperament of the pianist. At one end of the scale are pianists who play safe, in the interests of veracity, and who achieve an accuracy somewhere in the region of 97 to 99 per cent, depending on the difficulty of the piece they are playing. Such pianists are sometimes praised by the critics for their mastery and often condemned for their lack of musical persuasion. At the other end of the scale are pianists who are prepared to take risks - and sometimes pay the penalty. Their accuracy is perhaps around 90 to 97 per cent, again, depending on difficulty. These pianists are sometimes praised by the critics for their exciting, fluent playing and usually maligned for their mistakes (critics are like that). In each of these cases the pianist has chosen a value of selection accuracy and balanced the other variables against it.

8.1 THE PHILOSOPHY OF THE OPTIMUM MOVEMENT

Assuming a set of performance specifications for a passage has been decided upon and a criterion constructed, subconsciously or otherwise, then in theory the pianist has to discover the best movement for every note in the passage. Mathematically this can be achieved by writing the biomechanical equations for every part of the arm, and then using optimisation techniques to find out which are the optimum trajectories of each link of the arm and what are the appropriate switching signals of each muscle.

8.2 THE PHILOSOPHY OF STRATEGIES

Let us pause to consider what a mechanical optimisation would involve. Each link of the arm has several degrees of freedom, and there are some nineteen links in each arm, including the shoulder girdle. There are numerous muscles, with complex mechanical properties which are strongly dependent on such things as fatigue. In addition there is a network of connective tissue, which has a considerable effect on arm movements. Even if one had a complete set of data for all these components, the mathematical and computing effort needed to find the optimum way of playing a note would be gigantic - assuming one could find a sufficiently large computer. Then one could proceed to the next note.

But just suppose that such a tour de force were achieved, and the absolutely optimal movements were worked out for a short passage. The pianist would then be faced with the task of learning the movements, and would be doing well if he managed to complete this within half a lifetime.

This discussion should have shown that the philosophy of optimisation, although academically sound, is for practical purposes utterly useless. What is needed is a set of highly suboptimal movements, and if performance specifications suffer, this cannot be helped. Convenience, although frowned upon by some writers on piano technique, is itself a variable similar to those of the performance specifications. (To be pedantic, one might argue that the suboptimal solution is really an optimal solution with convenience as an extra variable - and strongly weighted).

In practice, then, one should aim for as much standardisation as possible. A standard finger movement should be developed, to be used whenever possible. As many links of the arm as possible should be held stationary so that dynamically they are, as it were, kept out of the way. The simplest switching signals to the muscles should be used, with bang-bang control the ultimate in desirability. In short, for a given technical problem (of the sort discussed in Chap.1), one should decide upon a strategy which is as mechanically simple as possible without compromising the performance specifications too much. The only case in which anything approaching an optimal set of movements should be used is in the sort of extreme examples given in Sec.1.9, and a dozen or two of these special solutions should be enough to cover the repertoire of most pianists.

Of all the writers discussed here, Ching comes nearest to adopting a deliberate policy of using strategies rather than optimal movements.

9

MORE COMPLEX MOVEMENTS

9.0 INTRODUCTION

In Chap. 7 we looked at playing the piano by means of arm actions. In this chapter, finger actions will be studied, but because these actions are so complex a mathematical analysis will not be attempted. Instead a more freewheeling approach will be taken, relying on the general principles so far deduced; and of course the concept of strategies will be used throughout.

Discussions of finger actions form the major part of the books on piano playing reviewed in this thesis. These discussions taken as a whole are concerned with the following variables:-

1. The degree of curvature of each finger under normal playing conditions.
2. The kinematics of the finger during a finger action.
3. The muscular exertion used to produce a finger action.
4. The height of the wrist above the keyboard.
5. The distance of the fingertips from the edge of the keys.
6. The degree of turning (in a horizontal plane) of the hand about the wrist.
7. The angle of the forearm (in a horizontal plane) with the keys.

8. The degree of twisting of the forearm.

9. The kinematics of the forearm and upper arm during each key depression.

10. The vertical, lateral and torsional stabilising forces exerted by the forearm.

11. The degree of rigidity of the wrist.

In addition to these variables, there are the variables of general key descent, discussed in Chaps. 6 and 7, to be taken into account.

The variables listed here will be discussed throughout this chapter, the order of development of the chapter being that of increasing complexity, starting with finger movements and ending with the playing of scales, arpeggios and other figures.

9.1 THE DYNAMICS OF THE FINGER IN PIANO PLAYING

One of the greatest fallacies encountered in reading books on piano playing is the assumption that the dynamics of a finger are the same whether or not the finger is depressing a key. Here is Gat:

> "In playing with stretched" (i.e. straight and near-horizontal) "fingers it is easier to attain soft tone-effects because the fingers are - as it were - elongations of the keys. In this position small movements of the muscles bring about large movements of the finger-ends. Muscle-activity is thus less tiring, which is of great advantage both from the point of view of velocity and of tone-intensity.
>
> In bent position comparatively great muscle-activity is required for the execution of small movements. That is why control and domination of the fingers is easier in this position."

In fact, a piano key presents considerable loading for the finger; it is true that in mid-air less force is needed for a given displacement when the fingers are straight and horizontal, but at the piano the situation is reversed, because the leverage of straight fingers is most unfavourable, as will now be shown.

In considering the finger/key system (taking the hand knuckle to be stationary or nearly so), the crux of any dynamic analysis is that the moment of inertia of the finger is very much smaller than that of the piano key. Thus one can analyse the system fairly accurately by using simple leverage principles. Suppose that we now compare the finger in two different states, state one being where the finger is fully extended, and state two being where it is curved so that the distance between the finger tip and the hand knuckle is only half the extended length. The muscles lowering the finger exert a moment on the finger that is virtually independent of the degree of curvature of the finger, hence the amount of force delivered to the key by the fingertip for a given muscular exertion is about twice as great in state two as in state one. However, the angular displacement of the base of the finger must be about twice as great in state two as in state one (assuming the fingertip to be at the same point on the key in both states), which means that state two needs a greater displacement of muscle and hence incurs a greater viscous resistance. However, this viscosity (for which we have no data) is unlikely to offset the force advantage of state two by any appreciable amount because the displacements, and hence velocities of extension, of the finger muscles are only small. On balance then, we can say that, the more curved a finger is, the more muscular strength it can display in depressing a key; and of course, the amplitude of sound produced depends on the force applied to the key, and has nothing to do with the velocity of an unloaded finger.

Another point which has been universally misunderstood is that the muscular strength of a finger (which we have just discussed) is not the same as its structural strength. A finger consists of three bones connected by tissues. Obviously the finger shows the greatest structural strength in depressing a key when it is fully extended and vertical; in this case the bone structure acts as a column. The finger is structurally weakest for key depression when it is fully stretched and horizontal (assuming that only the tip is in contact with the key), because in this position the bones are supported only by their connective tissue and the antagonistic muscles of the finger have to exert a lot of tension to hold the finger together. The structural strength of a well-curved finger is quite good, as the bone structure is then analogous to an arch.

As for the kinematics of finger actions, it is generally agreed that a key should be depressed by a movement which results in an increase of the curvature of the finger. Only Matthay makes an exception to this rule and advocates the occasional use of a finger-stroke which decreases its curvature. He seems to think that this affects the quality of the tone produced, but after the discussion of Chap. 6 we can see that this is almost certainly incorrect. There seems no reason to disagree with the consensus of opinion on this point, but I can think of one case where a finger-stroke of decreasing curvature might solve an awkward problem. This is in Ex.10 of Sec.1.9 where such a movement, as applied to the first in each pair of repeated notes would help prevent digit 2 from getting in the way of the oncoming digit 1 which takes the second note of the pair.

9.2 THE MUSCULAR CONTROL OF FINGER ACTIONS

We saw in Chap. 3 what a complicated set of muscles control the fingers. Most writers are not prepared to attempt any analysis of the workings of these muscles. However, Schultz goes into enormous detail and considers all the different combinations of muscle action. Unfortunately his arguments are unsound, being based on the sort of fallacies just described and containing some incorrect dynamic analysis.

Whether the choice of muscular coordination for a given movement and a given force output is important in piano playing is hard to say. Certainly for a passage needing strength, one should use all the muscles available, but for a quiet passage it is possible that one set of muscles gives better control than another. An analysis of the action of the finger muscles would of course be extremely difficult, as so many factors have to be taken into account.

9.3 FINGER PASSAGES : CLOSELY PACKED

Having considered finger action in general, let us now study the problem of playing a sequence of notes by finger actions, that is, a finger passage. Reference to Sec. 1.5 shows that, where finger passages are concerned, we can consider two types of structure : closely packed and widely spaced passages. (By convention, "finger passage" usually refers to a single sequence of notes - double sequences are usually treated as special cases, as are trills, shakes and repeated notes). The distinction between closely packed and widely spaced passages is of course rather arbitrary, but basically the criterion is that a widely spaced passage is one which necessitates a distinct stretching apart of the fingers. In addition to structural considerations, there are dynamics to be taken into account. In this section, closely packed passages will be discussed and the dynamics will be taken to be normal, that is, all the passages are to be played legato, at moderate amplitude, and evenly.

If a passage is closely packed, it follows that the forearm is not used to make lateral movements i.e. movements along the keyboard. There may be a small amount of lateral stability needed, but this is easily provided by a slight lateral firmness in the arm. The questions to be asked, then, are: how much vertical control and twisting movement of the arm is needed, and how much firmness should there be at the wrist?

9.3.1 The Self-Supported Arm

The simplest strategy to understand theoretically is that in which the arm and hand are held rigid both vertically and torsion-wise by antagonistic tension, so that the hand knuckles are fixed points. Then any key within the closely packed range may be played by selecting an appropriate finger and using a standard finger action. This strategy is often called that of a "self-supported arm", though only Ching gives a reasonably clear definition of it. In practice, of course, it is impossible to fix the hand knuckles absolutely - there must always be a reactionary movement. Ortmann is very worried about this motion, but we can see from the discussion of Sec. 6.2 that the properties of amplitude levels are favourable to the control of this reaction in that a violent movement of a finger produces a relatively large upward movement of the hand due to the reaction of the key, and that a gentle movement of the finger has little effect on the hand. Thus, a violent movement is more likely to suffer from a lack of control, but a violent movement produces a loud note, and the ear is less sensitive to variations in amplitude at this level. Hence, a reactive movement of the hand, provided that it is kept reasonably small, is of little consequence. This is an illustration of how strategies should be designed to match the properties of the ear.

Clearly the self-supported arm is a workable proposition for closely packed passages at normal dynamics, and it is in fact recommended by Ortmann, Schultz and (perhaps) Matthay and Gat. Is it then the best strategy? The answer is almost certainly no, for the following reasons:-

1. All the work of key depression must be carried out by the fingers; hence fatigue is a great problem. Moreover, the arm must remain fairly rigid and is prone to fatigue, particularly of the nervous kind.

2. The technique is very dependent on the kinematics of the finger actions and on the level of the forearm. Any deviation from a standard position or movement is likely to cause an amplitude error.

3. As each finger is constructed differently, five different sets of movements must be learned.

4. A legato can be produced only by the very careful timing of both the upward and downward movements of the fingers.

9.3.2 Irrotational Pressure Transfer

Most of the disadvantages of the self-supported arm strategy can be overcome by using instead the strategy of irrotational pressure transfer. Pressure transfer strategies (three appear in this thesis) have been completely misunderstood by Ortmann and Schultz. Ching, who is the enthusiastic proponent of irrotational pressure transfer, seems to have a reasonable understanding of what he is saying, but glosses over some of the details. I will now give what I hope is a complete explanation of what Ching is aiming for.

Consider firstly a simple problem in two dimensions (Fig.9.3.2.1). Here, a large mass of weight W is attached to and supported by three vertical columns. (As the problem exists in two dimensions, we are assuming some suitable arrangement giving stability in the plane depicted, without interfering with the reaction forces - for example, a pair of perfectly smooth restraining walls). Now if the floor is perfectly level and flat, the reaction in each column is W/3. If however the central column is shortened at the bottom by a very small amount then, assuming the mass W to be rigid, the force in the central column becomes zero and the force in each outer column becomes W/2. In other words, the central column no longer supports the weight.

Now consider a similar situation with the arm/key system. Suppose that note A is glued down to the keybed and note B is fixed so that it cannot move downwards from its undepressed

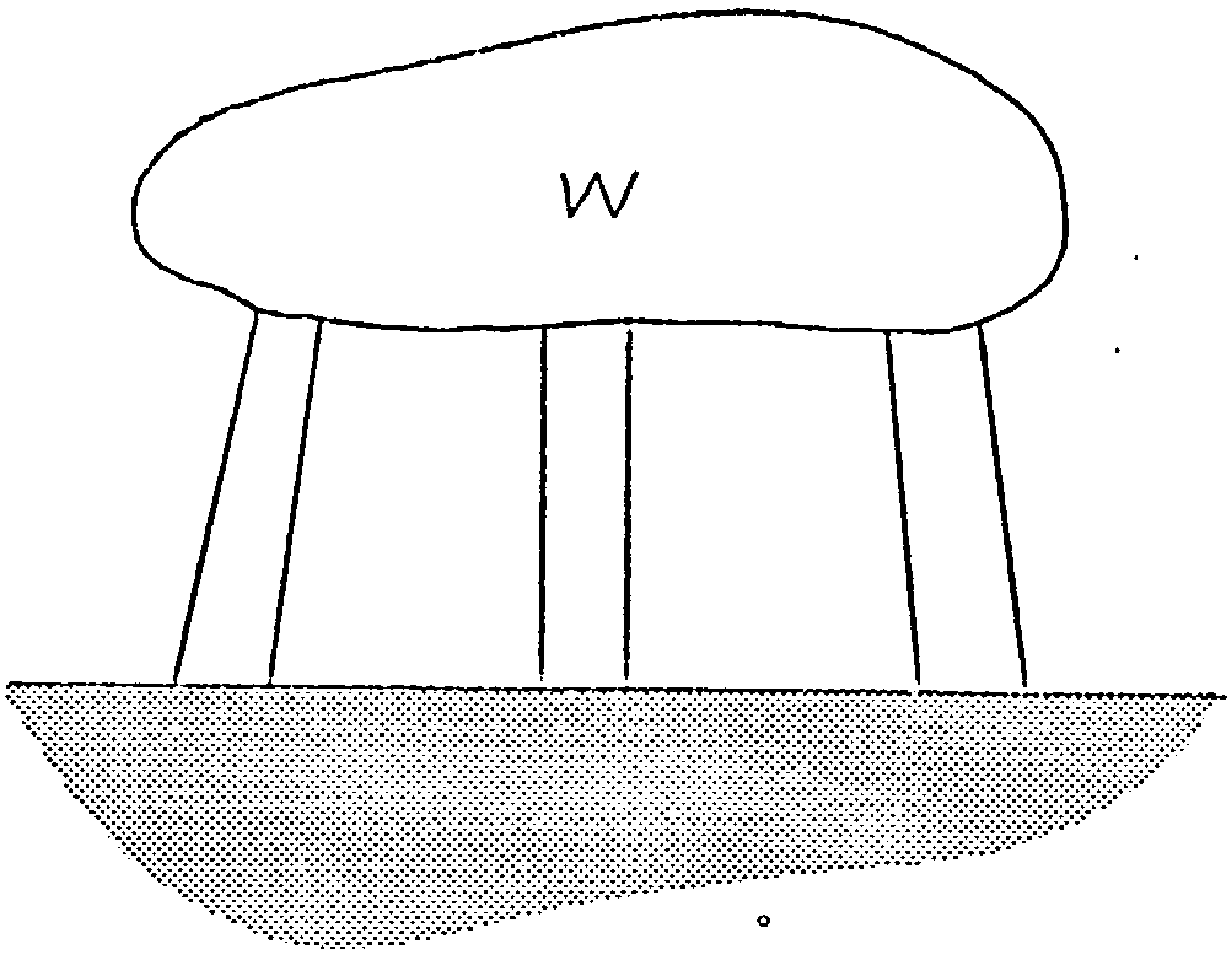


Fig. 9.3:2.1

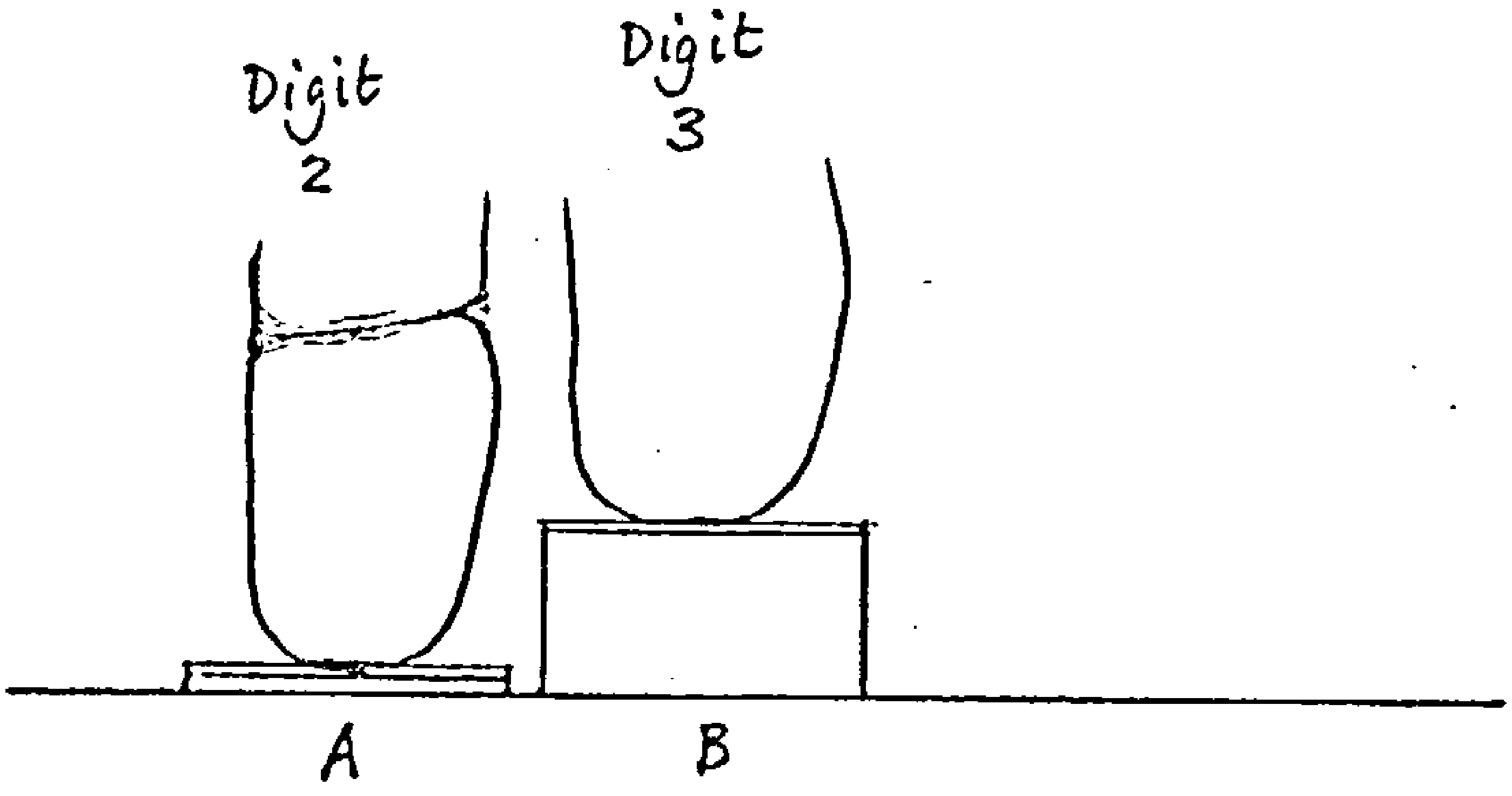


Fig. 9.3.2.2

level (Fig.9.3.2.2). Suppose initially that digit 2 of the right hand rests on key A and that digit 3 is held so that its tip is a very small distance above key B. Suppose further that the arm is being held in a stable state, laterally and torsionally, by means of antagonistic contraction, and that it exerts a force W downwards. Assuming that both fingers are in a firm state then it follows that digit 2 carries the force W, which is transmitted to key A. Now suppose that digit 2 is moved upwards about half a millimetre by muscle action. Then all the force W is immediately transferred to digit 3, which makes contact with key B. (The finite, rather than infinitesimal movement of digit 2 is necessary to allow for the inevitable slight sag of the hand as digit 3 takes the strain). Digit 2 is now free to move up or down at liberty - the force transmitted by digit 3 will be unaffected. (Actually, there will be a small reaction due to the upward acceleration of digit 2, but this is not appreciable).

For the next stage of the analysis, suppose that note B now behaves like a normal key (but note A is still fixed down). In this case, the force W, as transmitted through digit 3, accelerates the key B downwards, and the usual inertial equations apply.

Now suppose that both keys are free to move as normal. The situation is similar, but now digit 2 has to move upwards to the surface level of the keys, otherwise there is a danger that the force W will be transmitted back in part to key A. As the situation stands, the hand will sink by about a centimetre as digit 3 takes the strain. Therefore, in order to have irrotational pressure transfer as a workable strategy, it is necessary to keep the hand at a constant level. To achieve this, each finger, as it takes the strain, must move downwards relative to the hand through the distance of the key descent. Thus the strategies of irrotational pressure transfer and the self-supported arm are kinematically virtually identical.

To produce the downward pressure of the arm, the downward acting muscles of both the elbow and wrist must be in operation. The antagonistic muscles of these joints could also be applied to give a degree of stiffness, and so for that matter could the finger muscles, but theoretically this is not necessary. It must also be emphasised that in Ching's irrotational pressure transfer technique, the arm is to be kept unmoving torsionally. This can only be achieved by antagonistic contraction of the muscles controlling torsion. It is by no means easy to keep such stability, as digits 1 and 5 exert a large twisting moment about the forearm. Indeed, this is a major disadvantage of Ching's technique.

In assessing this technique, it is important to note that the pressure of the arm is passed on smoothly from key to key, and hence remains constant (or, at least, continuous - see Sec.9.8). Matthay describes a rather similar technique, but in which each note is given a separate stabilising impulse by the arm muscles. This is another case of Matthay ignoring time limitations.

Because in Ching's technique the pressure is passed continuously from key to key, the resulting sound texture is always legato more or less automatically; this is one of the great advantages of any technique which uses pressure transfer. (Strictly speaking, the technique gives the opportunity of producing a legato - a legato fingering does not always give a legato effect - see Sec.1.4).

If, in our earlier example (where the keys acted normally), digit 2 had not risen but merely relaxed, then the pressure would have passed on to digit 3, but note A would still have been held. The result would have been an overlap of legato; this modification of the technique gives us a simple way of controlling legatissimo textures.

As for the finger and hand posture of this technique, clearly the wrist must be at a moderate level (i.e. just above the surface of the keys) to enable the fingertips to move up and down under the action of the finger muscles. We have seen that straight, horizontal fingers are both muscularly and structurally weak, and so, when this technique is used, the fingers should be well-curved, which is Ching's recommendation. Ching also stipulates that the forearm be kept always parallel with the line of keys; this is in the interests of standardisation.

In Ching's view, this technique is virtually automatic in producing legato and a constant amplitude level, as all one has to do is to maintain a constant arm pressure whereupon everything will be taken care of. But here Ching is overlooking the fact that each finger must make a descent to preserve the posture of the hand. This descent needs muscular power, and therefore, as in the case of the strategy of the self-supported arm, the amplitudes of the notes produced by every finger descent have to be consciously matched, which means that a standard movement has to be learned for each finger.

It should be obvious that this technique depends entirely on accelerating the key down to the keybed (i.e. on keybedding), because the bed must carry the pressure in between key depressions. Other strategies, described later in this chapter, also use pressure transfer and are similarly dependent. This is partly why it was stated earlier that keybedding was a very advantageous policy.

9.4 FINGER PASSAGES : WIDELY SPACED

We have seen that the strategy of irrotational pressure transfer is reasonably satisfactory for closely packed finger passages. Now as the spacing of many of the finger passages which occur in the musical literature varies quite rapidly from close to wide and back, it is clearly very advantageous to have a strategy which works efficiently for any finger passage, regardless of its spacing. So irrotational pressure transfer, to be a really useful technique, must be a sound strategy for widely spaced as well as closely packed passages.

At this point I want to introduce a valuable observation of Schultz. It is that, as the fingers are spread apart, it takes more and more force to depress them, even when they are unloaded. One would guess that the reason for this is that the tissues between the finger-bones in the hand which help to bind the hand together have a certain amount of slackness in them; when the fingers are widely separated, this slackness is taken up and the tissues then act as extension springs.

And now for a second point. A really widely spaced passage cannot be executed with bent fingers - the fingers must be straightened as well as stretched apart, and if irrotational pressure transfer is used then they must become nearly horizontal. Now we have seen (Sec.9.1) that straight horizontal fingers have a poor leverage, and for this reason more force than usual from the finger muscles is needed for key depression. Furthermore, there must be some antagonistic muscle contraction to hold the fingers together in this position, as was discussed in Sec.9.1, and this in turn means that the finger muscles must work even harder in depressing the key.

Here then are three reasons why it takes more force to depress keys in a widely spaced passage as compared with a closely packed passage. Now these points are completely missed by Ching, and their consequences are most serious as far as irrotational pressure transfer is concerned. If the force needed to depress a finger depends on the spacing of the finger passage, then, for finger passages in general, the strategy of irrotational pressure transfer cannot be said to be a successfully standardised one at all, and it was this very feature of standardisation which made Ching's technique appear so attractive.

9.4.1 Rotational Pressure Transfer

Ching's irrotational pressure transfer strategy has been shown to be unreliable for finger passages in general. This does not mean however that the whole concept of pressure transfer is misguided. Fielden describes another form of pressure transfer, which will be called here "rotational pressure transfer". This is similar to Ching's strategy except that the arm is given much more freedom. Firstly, the forearm and hand are allowed to rotate about their axis to whatever angle is most convenient; usually it is most convenient to reduce finger movement to a minimum. (For example, a strenuous passage where the notes B flat and C are to be played by digits 4 and 5 respectively of the right hand can be ameliorated by twisting the forearm clockwise as soon as digit 4 descends, or perhaps a little before; this reduces the movement of digit 5, which, being a weak finger, must be protected against undue exertion.) It must be made clear that the hand still acts as a base for finger actions, but because it is not stationary, naturally it makes a contribution to the action of depressing a key, and hence the action of the finger itself must be modified to compensate for this. The result is a great loss of standardisation, which Ching was anxious to avoid. But the point is that, in general, Ching's strategy is not able to make use of standardised movements either, as we have seen, and hence Fielden's strategy may well be more reliable than Ching's. What can certainly be said is that Fielden's strategy is much simpler to perform and has a more natural feel to it because one no longer has to bother particularly about torsional rigidity - all that is needed is a slight amount of torsional stiffness, the magnitude of which is probably nowhere near critical.

In Ching's technique, the forearm is held in line with the keys for reasons of standardisation. But as the technique is impossible to standardise for general finger passages, there is little reason for holding the forearm in this position, and this constitutes a second difference between the strategies of Ching and Fielden. Fielden allows the forearm to move in a horizontal plane so that it does not necessarily lie in line with the keys. For example, if digits 4 and 5 of the right hand have to play notes a fourth apart, then, with Fielden's technique, the elbow should move outwards during the playing of the notes so that digit 5 becomes almost lined up with the forearm. Now this is a shrewd move by Fielden because, if the forearm is held in Ching's position, both fingers have to stretch sideways by a large amount, and most of their strength is taken up in overcoming the tissue resistance. When the forearm is moved as Fielden proposes, however, the fingers do not have to stretch excessively, and their strength is conserved; furthermore, their movements are nearer to being standard ones (i.e. the movements which would have been used if the passage had been a closely packed one).

Fielden goes on to say that this movement of the forearm is difficult because it is often jerky. It is his theory that jerkiness can be avoided by moving the wrist up and down at the same time so that the wrist, instead of moving only in a lateral direction, now describes an ellipse. Ching copies this idea and recommends it for really large stretches - ones which could not possibly be reached without some sort of forearm movement. Unfortunately, however, the addition of a vertical component of movement can in no way affect the motion of the horizontal component, and so, if rotational pressure transfer is used, this elliptical motion is not to be recommended.

When using Fielden's technique, it is important to move the whole forearm. If instead the hand is turned laterally about the wrist, with the forearm in the same position, then tendon strain will occur at the wrist, and produce a loss of standardisation.

9.5 FINGER PASSAGES : THE LIMITATIONS OF FINGER ACTIONS

Let us return for the moment to the subject of finger strength and uncover some more popular fallacies. In Sec.9.1 a distinction was made between muscular and structural strength.

Where muscular strength is concerned, digit 4 is the weakest finger; however, structurally, digit 5 is weakest. Both these statements of course refer to finger descent. But piano playing involves not only finger descent, but also finger ascent, and this is where complications arise. It was discussed in Chap.4 what happens to the forearm when it is engaged in rapid oscillation. As the fingers are controlled by skeletal muscles in much the same way as the arm, it is only to be expected that they suffer from similar problems. In the case of the arm, the limitations of the skeletal-nervous system become apparent when the oscillation rate is something of the order of 5Hz, and beyond this the oscillation rapidly becomes choked. As a rate of 10 notes per second is nothing out of the ordinary in a finger passage, then clearly we have to consider the available strength of a finger rather than its gross strength. In fact, finger strength, or weakness, is ultimately a function of the order of succession of finger movements, and hence it is a function of the music itself. Reference to Fig.3.1.1.2 shows that the succession of digits: 3-4-3-4- ... is, mechanically, very awkward; indeed, it takes the full strength of the muscles of these fingers to execute this sequence on a keyboard without rocking the hand even at a moderate speed. (The first two notes are perfectly easy to play; it is the third and subsequent notes which are difficult).

Fig.3.1.1.2 shows that the tendons of digits 3 and 4 suffer from a lack of independence. But there are further reasons for the difficulty of finger alternation in general. As we saw in Sec.3.1.1, there is a common-user muscle, the extensor digitorum communis, for lifting the fingers. Now in a rapid alternation, there is little difficulty in lowering the fingers, but presumably this common muscle has to operate for every lifting movement (although it receives some help with digits 2 and 5). Clearly then this is the limiting factor in finger alternation; the common muscle must become "jammed" even at quite low rates of alternation.

One could construct a list showing the relative difficulty with which pairs of fingers can alternate; the pair 4-5 is next to the pair 3-4 in difficulty, and probably the pair 1-3 is the least difficult of all. None of the writers considered here seems to have fully grasped this idea.

All this is another nail in the coffin of irrotational pressure transfer, although Ching is oblivious of it. He even criticises another theoretician for using the sequence of digits 4-2-3 (right hand) on the notes G-F sharp-G in a rapid Mozart passage and changes this sequence to 4-3-4, whilst recommending irrotational pressure transfer for playing it. Unfortunately, rotational pressure transfer can do little to help this sort of difficulty either, so we must continue our search for a more versatile finger passage technique.

One last point. In a very rapid passage, where the fingers have to be used in an awkward sequence (i.e. involving unfavourable repetition of fingers), it may become necessary to temporarily sacrifice keybedding and hence some elements of pressure transfer, as the fingers may only be capable of descending a few millimetres in the time allotted, due to the muscular and tendon resistance.

In the next few sections, finger passages (i.e. of arbitrary spacing) will be examined under differing dynamic conditions.

9.6 FINGER PASSAGES : THE CONTROL OF FORTISSIMO

As was mentioned in Sec.7.0, the muscles which operate the fingers are not as strong as those of the arm. Consequently, in the playing of loud finger passages, fatigue is a great problem, and can set in very rapidly. Fortissimo finger passages must therefore be treated as a separate problem.

Matthay refuses to recognise the problem, declaring that "it always takes precisely <u>the same amount of force</u> whether you move the key slowly or quickly", his reason being that "it takes the same amount of force whether you walk or run upstairs". Ching gives as his solution the strategy of keeping the wrist in a very low position. His reason for this is that, if the wrist is in a very <u>high</u> position, the tendons of the finger suffer strain at the wrist during a downward finger action, and fatigue occurs more easily. This is perfectly true, but Ching's deduction is not, because if the wrist is in a very <u>low</u> position, then the tendons suffer strain during the <u>upward</u> finger movement. This sort of thing, as we have already seen, always happens when an extreme position is taken. There is no reason why the wrist should not remain in an average position i.e. just above the key surface. In this position there is little tendon strain at the wrist. Actually, it is possible that Ching has been misled by one of Ortmann's silly calculations which purports to prove that a low wrist position gives a better transmission of the pressure of the arm. The whole question of arm pressure, though, in this context is a red herring. The point is that the arm can easily exert sufficient pressure to make a very loud note. (In Wilkie's experiment, Chap.3, 200N was the order of magnitude of the maximum force exerted by the elbow muscles at the hand - this is enough to smash a piano).

Apart from tendon strain, there is another disadvantage in keeping a low wrist. In playing scales and arpeggios (discussed later), if the wrist is low, the passage of the thumb will be impeded.

Ching gives a further strategy for fortissimo playing. He argues that the amount of force delivered by pressure transfer can always be increased by raising the fingers well above the level of the keys and striking each note down (i.e. with impact) as it takes the pressure. Again, this idea ignores the fact that there is no shortage of arm pressure. It is a serious mistake to raise the fingers in a fortissimo passage, as this means that, because of the extra movement involved, fatigue occurs much more quickly.

9.6.1 Rollbewegung

Now let us turn to an old and much-despised strategy, that of "Rollbewegung" (rolling-motion) developed by the German school with Breithaupt as its chief proponent. All the other writers regard this technique as disastrous, although most of them have completely misunderstood it. Breithaupt gives only a sketchy account of the method, so there now follows a detailed explanation of it.

Consider first a two-dimensional situation in a vertical plane where a body shaped as shown (Fig.9.6.1.1) rests on a rough, level surface and is acted on by a horizontal force F at height h, and a downward force W acting above the point B. When a positive force F is applied, the body rotates about B through a small angle

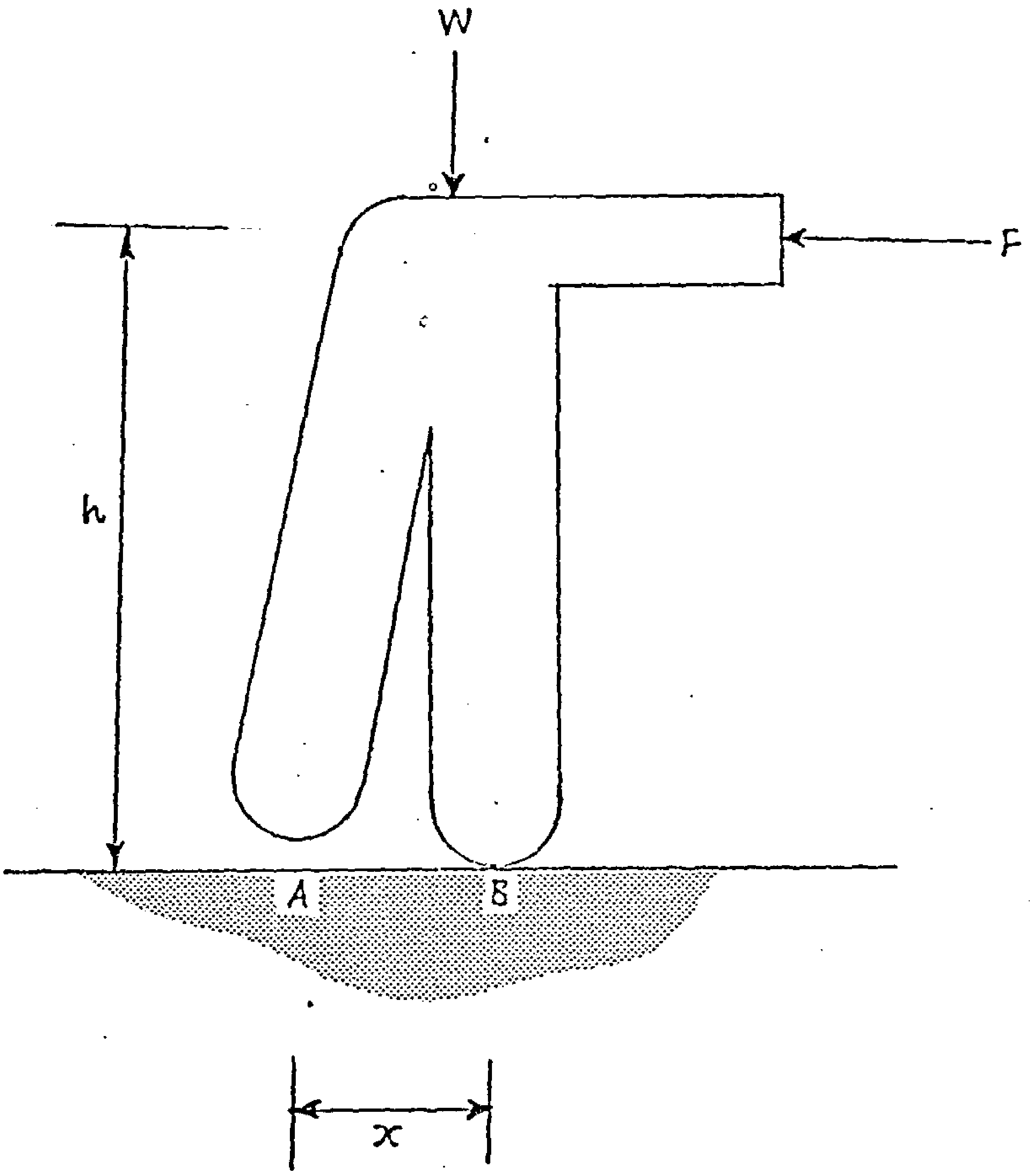


Fig. 9.6.1

and makes contact with the ground at A. If the contact force here is P, then taking moments about B, approximately

$$P = Fh/x$$

which means that, when the ratio h/x is large, the force F is magnified substantially. If the force F continues to be applied, rotation occurs about A, contact is lost at B, and the force W is transferred to the point A.

Now we can extend this idea to the arm, and consider rolling from one finger to another when the fingers are straight and vertical. In this position virtually no muscular effort need be applied to the fingers themselves, as all their strength is structural. The sideways-acting force, F, is provided by the forearm, which has great reserves of strength for this motion.

This action can be used to play finger passages, although there are obvious difficulties in keeping the fingers vertical. However, provided that the wrist is kept relatively high and the fingers fairly straight, then the sideways force of the arm can still be used, and not much force from the finger muscles is needed to give the fingers sufficient strength. Actually, in playing with this action, a slight finger movement is usually necessary to put each finger into a suitable position for depressing the desired key.

The technique of Rollbewegung just described is rather similar to Fielden's rotational pressure transfer (Fielden thinks it is identical), but the difference is that in Fielden's technique, the arm and hand rotate to serve as a convenient base for finger actions, whereas in Rollbewegung, the arm and hand provide most of the key-depressing action (and therefore they must move rapidly during the depression). Furthermore, the wrist is higher in Rollbewegung than in Fielden's technique. All the same, as the wrist level comes down, the action of Rollbewegung is gradually converted into the action of rotational pressure transfer with minimal finger action.

It seems that Breithaupt's strategy is by no means as bad as is commonly supposed. Its great advantage is that the ratio between the force applied to the key and the force exerted by the finger muscles is larger than that of any other method, because there are two transferred forces: the usual downward pressure and also the sideways force of the arm and hand. Thus this strategy is most useful for passages needing strength or stamina. The disadvantage of the technique is that there is a loss of standardisation; however, in a loud passage (where it would normally be used) this loss is not so important, as we have seen.

A further extension of Rollbewegung is as follows. Consider, as a model, a sphere with numerous pins inserted. This sphere can be rolled from pin to pin in any direction. Similarly, the hand can execute a rolling motion in other directions than that of side-to-side; the backward-and-forward component of motion (involving an up-and-down movement of the wrist) can be added in any quantity as desired. The technique is obviously very versatile and can solve many problems where power is needed in awkward positions; it can also help in some of the awkward finger sequences mentioned in Sec.9.5. Breithaupt is to be commended for having an intuitive grasp of its essential features.

9.7 FINGER PASSAGES : THE CONTROL OF PIANISSIMO

We have seen (Sec.6.2) that amplitude sensitivity increases as amplitude decreases. Many writers give special techniques for dealing with the problem of very soft finger passages. Ching's strategy is to raise the wrist abnormally high, so that the fingers become straightened. This position, he says, gives better control of the finger actions. His reasons for this are that, firstly, because of the tendon resistance of the high wrist (Sec.9.6), the movements will be "mechanically limited", and, secondly, because the leverage of straight fingers is less favourable than that of bent fingers, a given amount of muscular force produces less amplitude.

It seems that what Ching has in mind is that there will be an attenuation of the normal finger action, and that this will cause the errors in amplitude of the muscular force applied to be diminished at the output. This, however, is a dangerous concept. It is not necessarily true that the force-amplitude sensitivity of a muscle is independent of amplitude; in fact, the general ability of a muscle to judge force is usually considered to be something of a Weber-Fechner relationship. Furthermore, Schultz makes the valuable observation that fingers in this position spread out radially; that is, the spatial sequence of fingertips: 1-2-3-4-5 lies approximately on the arc of a circle, whereas, for example, in the curved-finger posture with normal wrist height, the fingertips lie almost in a straight line. Thus, in Ching's position, the leverage of the fingers is completely altered from the norm. If one wished to use this strategy, it would be necessary to learn a completely new set of movements for the fingers; but playing a pianissimo passage is the very occasion when one wants to rely on well-known movements, because the control of amplitude is so difficult. In short, there does not seem to be any merit in using for a pianissimo finger passage anything other than the usual strategy for finger passages.

9.8 FINGER PASSAGES : THE CONTROL OF EVENNESS AND ACCENTUATION

In discussing finger passages earlier, the problem of keeping the amplitude at a constant level was encountered and solved reasonably satisfactorily. Now let us consider the problem of controlling fluctuations in the amplitude level (Sec.1.7). An even (i.e. continuous) variation is not a severe problem, and it can be controlled by a pressure transfer technique - all that is needed is that the pressure be smoothly altered by the arm muscles.

However, the problem of accentuation cannot be solved by pressure transfer. For this an arm action is needed, that is, a definite vertical movement of the forearm about the elbow for the accented note, followed immediately by normal pressure transfer for the remaining notes. Those authors who favour pressure transfer techniques are usually agreed on this point. Ching states his case clearly and, as already mentioned, gives as an order-of-magnitude estimation, a figure of 50% arm actions and 50% finger actions when playing the piano. (These figures apply to all passages taken together, not just finger passages).

Although even fluctuations can be controlled by altering arm pressure, Ching gives a modification to his irrotational pressure transfer strategy, which he calls the "undulating wrist" technique and which he believes gives better control than varying arm pressure. This technique is similar to his basic strategy, but the wrist, instead of staying at a constant level, moves up and down, a "down" movement causing a steady increase in amplitude and an "up" movement causing a steady decrease - at least, according to Ching. Ching says that the advantage of this technique is that the arm pressure need not be altered, as there will be an automatic change in the fingerstrokes which will cause the required amplitude change. His reasoning is that the up-and-down movement is a combination of his two previous techniques for the control of fortissimo and pianissimo, but we have seen that these techniques are suspect. Certainly, this up-and-down technique has the usual disadvantage that because the kinematics of the finger actions alter as the wrist rises and falls, there is a loss in standardisation. It seems wiser to keep the wrist level constant, and alter the arm pressure.

Harrison also describes an up-and-down movement of the wrist, but there is no obvious reason why this motion is in any way helpful.

9.9 FINGER PASSAGES : THE CONTROL OF STACCATO

It is clear that any of the pressure transfer techniques, whether Ching's, Fielden's or Breithaupt's, gives virtually automatic control of legato. But the control of staccato is not so easily won; pressure transfer techniques cannot be used because these techniques always give a legato; therefore, some other technique, such as the self-supported arm, must be used. If pressure transfer is not used however, then most of the control of evenness is lost, and so one is left with the problem of managing both the staccato and the evenness.

Ching recommends that at relatively slow speeds any staccato passage should be played not by finger actions at all, but by a series of arm actions. This is good advice and in keeping with the philosophy of standardisation, because the problem of matching the amplitudes produced by five different fingers is now replaced by the simpler one of matching the amplitudes produced by one arm. Of course, above about 8 notes per second, arm actions cannot be used, but Ching has a theory that at about this speed a sort of "persistence of hearing" occurs, above which the ear can no longer detect a staccato, making the problem of producing a rapid staccato a redundant one. This does not stop him from giving a technique for producing disconnected notes in rapid succession; the result, he says, is a "non-legato". His method is to use the basic self-supported arm strategy, but in addition to lift the fingers well above the keys and strike them with an impact.

Now after the analysis of Chap.6 we can see that this strategy is not a sound one. Firstly, there is no point in raising the fingers to give an impact start because, as we have seen, it is not possible to alter substantially the descent of the key and still preserve the same level of amplitude. Secondly, all staccato techniques must produce a rapid reversal of the key movement, as discussed in Sec.6.3 and Ching's technique involves reversing the motion of each finger, which is certainly a tricky thing to do, especially when one considers the physical limitations of the muscle-tendon system of the fingers. In any case, it is doubtful if this method could be made to produce a staccato passage of high amplitude because the common lifting muscle of the fingers must be in constant operation and must therefore inhibit the descent of each finger. (Bear in mind that there is no arm pressure behind the fingers).

9.9.1 A New Technique for Staccato

A new technique is now proposed for staccato finger passages (or "non-legato" in Ching's estimation), which avoids the previous problems. The basic strategy is that of the self-supported arm (this cannot really be avoided for staccato). The wrist should be in a rather high position with the fingertips at key level. All that is necessary for a good staccato, loud or soft, is for the fingers to execute a stroke which carries them down with the key and immediately on into a considerably curled position. This gives the key the required down-and-up movement, but - and this is the important point - the fingers do not have to reverse their motion.

This technique is satisfactory for the fingers proper, but not for the thumb. For this digit one can either use a normal stroke and tolerate the resulting loss of staccato, or arrange the position of the hand so that the thumb slips off the front edge of the key into space as it executes a downward stroke.

If this technique is used it is probably wise to sacrifice the policy of keybedding.

9.10 FINGER PASSAGES : A REVIEW

We have reached the end of the discussion of finger passages. In order to present a logical development it has been necessary to omit many of the interesting statements made on the subject in the literature. To partly make up for this, here are some of my favourites, which, for the most part, speak for themselves.

1. Gat, in discussing the strength of each digit, makes the following pronouncements:-

Digit 2: "its agility ... leaves much to be desired, because (it) is overburdened to the utmost and stiffened by the movements required in everyday life (holding, grasping, pressing movements), and this detrimentally affects its work in piano playing"

Digit 3: "precisely on account of its length, it is inclined to become passive"

Digit 4: "The striking force of the finger is proportionate to its length, and its agility even surpasses that of the other fingers"

Digit 5: "one of our most muscular fingers ... Its strokes, however, are weak on account of its shortness and small mass".

2. Gat confides with his readers and informs them that the secret of playing all finger passages is to use his own "adapting" and "synthesising" movements. Gat explains what these wonderful actions can do (just about everything imaginable) but is so carried away in his enthusiasm that he forgets to define what they are, so we are none the wiser.

3. Schultz declares that the playing of a finger passage both rapidly and loudly is impossible - which indeed it is using his methods. But one only has to listen to almost any first class pianist to realise that in fact it is perfectly possible. All the same, Schultz maintains that it cannot be done "by even our greatest technicians". Now this raises an interesting point. Bree, Breithaupt, Ortmann, Fielden, Matthay, Ching and Gat all mention specifically the playing of several great pianists, and

in every single case with obvious admiration. But Schultz mentions nobody; one wonders in what sort of parochial environment Schultz carried out his investigations. Has he never heard a good pianist?

4. Matthay, having delivered a homily on the foolishness of trying to specify which muscles should be used for a given action, goes on to say that in a finger passage the finger muscles situated in the arm should be used to depress the key and the small muscles in the hand should hold the key down. (This is Matthay's idea of pressure transfer). The reason for this is that an oyster uses a strong (but fatigue-prone) muscle to close its shell, and a weak (but stamina-rich) muscle to hold it shut.(Sec.3.1 is highly relevant).

9.11 COMBINED ARM AND FINGER ACTIONS

There is a very important class of movements in piano playing which are neither wholly arm actions nor wholly finger actions but actually a mixture of the two. Some writers do not like to acknowledge their existence. Matthay for once is fairly explicit and gives a musical example where such movements should be used. There is no need to labour over a description of the movements. Simply, the fingers use their normal action and the forearm oscillates in coordination. But - and this is where writers go astray - the forearm does not move up and down as a reaction to the finger movements; it is driven by the elbow muscles so that the forearm and finger describe a combined stroke.

The advantage of using this strategy is that it enables a large tonal amplitude to be produced. In a legato passage it is just as effective as Rollbewegung; in a staccato passage, where Rollbewegung cannot be used, it is a very powerful technique, especially in widely spaced passages. The snag is, of course, that it can only be used at frequencies up to about 6 Hz.

9.12 LATERAL STABILITY

Previous writers have spent most of their energy in discussing the downward motion of the arm and fingers. They would have been better employed in considering carefully the problems of sideways motion. In looking at extreme examples such as Ex. 7 and Ex. 12, one cannot help but think that achieving accurate lateral movements is one of the most important and difficult aspects of piano technique. Yet virtually nothing seems to have been written on the topic.

The most difficult aspect of sideways motion is when a finger has to depress a key which lies some distance away in a very short space of time. In approaching the key, the finger must move rapidly sideways, which is bad enough, but the root of the problem is that, on reaching the key, the finger must decelerate sharply and immediately depress it; indeed, because time is in such short supply, deceleration and depression must be carried out together.

The problem is in fact one of lateral stability. The forearm must be used to carry the finger along, and therefore the muscles of the arm must be controlled in a bang-bang fashion. What is very important is the trajectory of the finger itself, and this will now be considered in detail. None of the authors reviewed here stresses the enormous difference between an awkward sideways movement which lands on a white key and one which lands on a black key. Take the case of a white key. Fig.9.12.1 illustrates digit 5 of the right hand landing on a white key (note B) after a leap. We can see that, as key B descends, the finger may slide with impunity into the side of key C; in other words, key C acts as a buffer to the leap and provides much of the deceleration of the finger. However, buffering can only take place if the finger is structurally stable; if the hands and fingers are kept in the usual playing position (i.e. in line with the keys), then it is very likely that the fifth finger will partly collapse and spill on to the next key. The solution is to turn the hand so that the finger is in line with its own trajectory. In this way, the structural strength of the finger is used to give stability; indeed, one may well use the third digit rather than the fifth for all leaps.

Now take the case of a black key. Fig.9.12.2 illustrates a finger landing on a black key in the way recommended for a white key. We can see that for the note A flat the finger is not properly buffered, and for the note B flat it is not buffered at all. In landing on any black key there is a great danger that the finger will overshoot the key and slide off on to the next white key. The only solution is to make the approach angle very low, that is, to land on the key with the finger almost horizontal.

It is taken for granted by all writers that the shape of the fingers during octave playing is the same whether a pair of black keys is being played or a pair of white keys. However, applying the ideas of lateral stability just developed, this assumption must be questioned. The white keys form a continuous surface, whereas the black keys form a discontinuous one. It

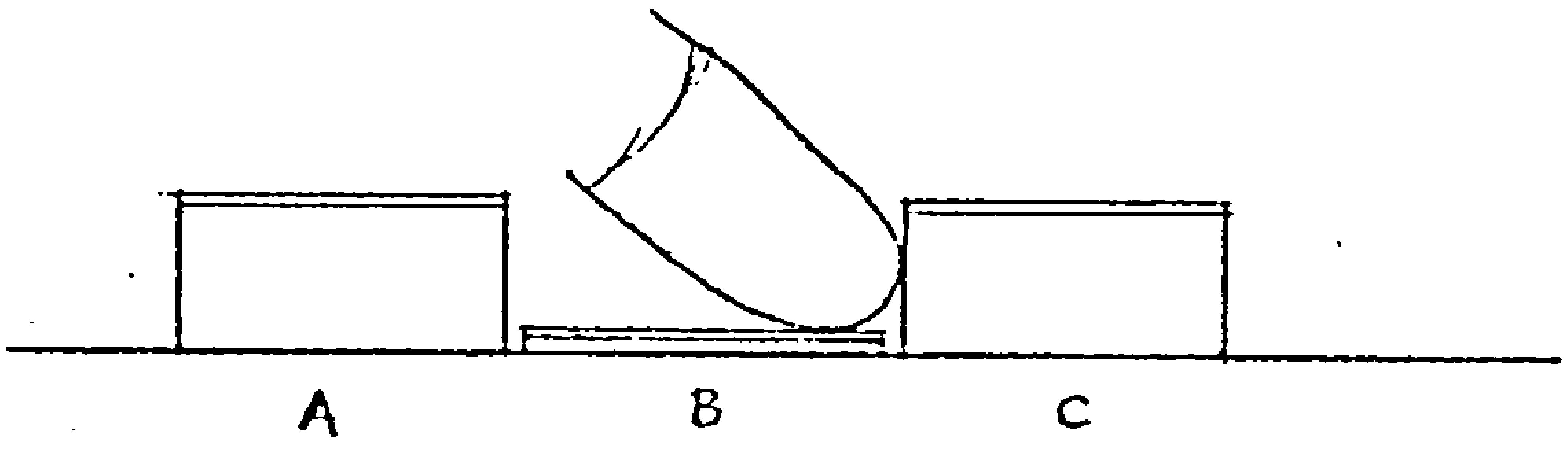


Fig. 9.12.1

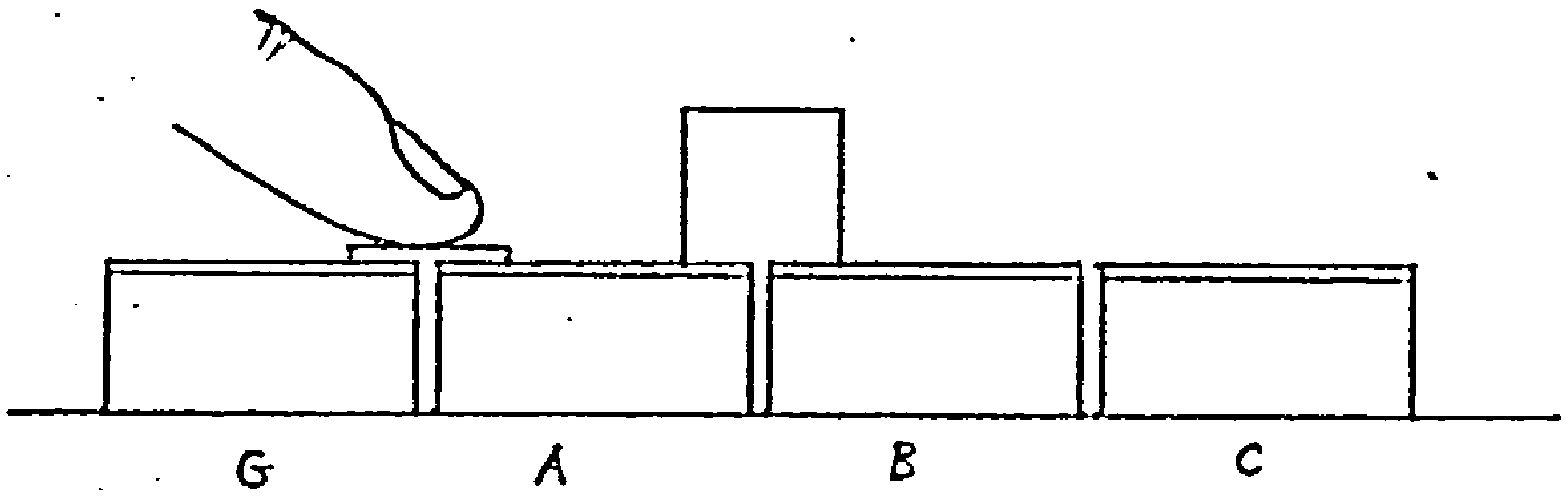


Fig. 9.12.2

follows that if an octave is played on the white keys, then the end phalanxes of the thumb and fifth finger should be curved inwards so that they are in line with the keys (this is not possible for small hands) to reduce the surface area of the fingertips to a minimum and thereby increase the chance of accurate note selection. If an octave is played on black keys, then the thumb and fifth finger should be splayed outwards at the ends to increase their surface area and hence minimise the risk of slipping off the keys.

Exactly how one should play such examples as Ex. 7 I do not know, but the material of this section can at least serve as a basis for analysis.

9.13 SCALES

An upward scale is almost invariably played with the following fingering (right hand): 123123412312341 ... or something very similar. It can be thought of as a series of closely packed finger passages, each of three or four notes, with a rapid shift between each one. It is this shift which is the chief source of trouble in the playing of scales.

Consulting the literature we naturally find much disagreement. Both Matthay and Schultz dismiss scales and arpeggios with a brevity which is breathtaking, no doubt presuming that if one note can be depressed properly, a scale should present no problem. The other writers all give highly incomplete descriptions of scale-playing. Taking their work as a whole, we find the following movements put forward. The fingers (digits 2 to 5) can be (1) used in the usual way - that is, with vertical strokes; or (2) given an added sideways component of motion so as to thrust the hand along in the direction of the scale (this action has some of the characteristics of a spider walking). The hand, in order to surmount the shift between each short group of notes, can move, (1) laterally about the wrist, whilst remaining horizontal; (2) move up and down about the wrist; or (3) twist, i.e. as an extension of the twisting forearm. The forearm, in the case of finger movement number (2) above, need provide no lateral force, as it will be carried along by the hand; in the case of finger movement (1), it should either (1) provide a continuous lateral force, or (2) provide a series of force pulses to coincide with each shift. The thumb, being capable of extensive sideways movement, is the digit which must carry out the shift; earlier writers assumed that the thumb could pass under digits 2 and 3 and carry on to its next note under its own power but later writers (Fielden, Ching and Harrison) say that although this can be done at low speed, at high speed it is impossible, and that in a fast scale the thumb should be jerked into position by the hand and arm.

The writers we are reviewing put forward various combinations of these movements as their strategies for scale-playing. My own choice would be as follows. In the interests of standardisation, movement (1) of the fingers should be used. Fielden, Ching and Harrison are probably correct in stating that the thumb must be jerked into position at high speeds, and because of this the question of lateral stability arises. If the arm were moved in a series of lateral jerks then it would be very difficult to achieve such stability - apart from anything else, the displacements of the shifts are normally in the ratios 3:4:3:4: etc. It seems wisest to produce a steady lateral force with the forearm. Turning the hand laterally to achieve a shift means that the fingers are swung into unfamiliar positions over the keyboard. Probably the best way of making the shift is to keep the wrist fairly high and give a sudden twist of the forearm which will swing the thumb into position. Now it is universal practice to finger scales so that the thumb always plays a white key; therefore the jerk of the thumb can be classed as an awkward rapid sideways movement which lands on a white key, and this is the topic which was discussed in the last section. In view of this we can see that the twisting movement of the forearm will be well-buffered by the next white key and hence the movement can be controlled quite well - certainly it is superior to a lateral jerk of the forearm.

To summarize: the strategy put forward here is to use normal finger actions for key depression, continuous lateral force from the forearm to give direction to the scale, and twisting pulses from the forearm to achieve each shift. This is, however, only a suggestion and really scale playing needs far more study than has been given here.

Scales in the reverse direction need different movements (i.e. mirror images will not do) but the same principles are involved.

9.14 ARPEGGIOS

The playing of arpeggios is in many ways similar to the playing of scales; whereas a scale is a series of short closely packed passages, an arpeggio is a series of short widely spaced passages. Arpeggios tend to be more difficult to play than scales because, firstly, the spacing of the fingers is wide, and, secondly, because the shift of thumb takes place over a wider interval.

(Usually the thumb shifts only once, rather than twice, per octave). Because of this wide spacing, and because there is a much greater variety of arpeggios than scales, we can see that the finger actions needed are very much functions of the music, and so any writer who puts forward one method of playing arpeggios is being somewhat over-optimistic. Furthermore, although rapid scales can be played without too much passing of the thumb, the wider gap which the thumb covers in arpeggios makes lateral stability more of a problem; some turning of the hand to assist the thumb is almost always essential.

All that will be said here is that there seems to be a case for a high wrist position in many arpeggios. This can be seen to be true by resting the thumb on a flat surface and rotating the hand from one playing position to the next without moving the thumb; with a low wrist it is impossible for the fingers to move far over the thumb; with a high wrist a much wider sweep can be achieved.

What is not always realised is that it is often quite unnecessary to use any special arpeggio strategy. Even first rate pianists can on occasion be observed to play slow (i.e. about three notes per second) and quiet arpeggios with the pedal held on, using a pressure transfer or similar technique and therefore an elaborate thumb-passing movement. This sort of technique is normally used to deal with speed, or strength, or legato requirements, but in the case just cited such a technique is quite pointless and, musically speaking, highly dangerous. A series of identical arm actions is much easier and far safer.

9.15 THE NERVOUS CONTROL OF FINGER PASSAGES

We have now looked at the basic structures of notes which occur in music. The rest of this chapter will be devoted to a few more advanced topics. In this section it is proposed to look at the way in which the nervous system controls finger actions during the playing of a finger passage. Matthay, as we have seen, expects the brain and the nervous system to do all kinds of things during a key descent, regardless of the fact that a descent takes place in a very small fraction of a second. Fielden takes a much more sensible view of nervous control. His theory is that in order to play a rapid group of notes, the appropriate signals to the muscles must have been preprogrammed en bloc as the result of long experience. Thus, for example, the group of notes ABCD can be rattled off by any pianist, because it is so familiar. However, the relatively uncommon group ACBD is almost impossible to play rapidly and evenly unless the pianist has in the past deliberately set out to learn this particular figure as a reflex action. Thus one aspect of the acquisition of skill is the building in effect of a library of nervous routines; the implications of this for the aspiring pianist are clear. This whole theory of Fielden's has a ring of truth about it, and it is probably his most valuable contribution. Certainly no other writer has made any reasonable alternative suggestion.

9.16 REPEATED NOTE STRUCTURES

As we saw in Chap.6, a note which is being rapidly repeated is in a different state, mechanically, from a nonrepeated note. This is due to the behaviour of the piano key mechanism, which enables the pianist to repeat a note using only the bottom three or four millimetres of the key descent. It is possible to repeat a note rapidly by letting the key rise fully, but in this case the action behaves sluggishly and none too reliably, as one would expect from studying a diagram of the action, and there is no doubt that the best policy for repeated notes is to keep the key always in the lower part of its descent.

This fact seems to have been almost totally ignored in the literature, but the implications are serious. Many finger passages contain a note which is repeated, and in order to play the repetition cleanly it is essential to catch it near the keybed.

More subtle is the fact that many finger passages contain a virtual repeated note. For example, the sequence of notes A-B-A does not, on paper, contain a repeated note, but if the sequence is played rapidly, then, as far as the piano mechanism is concerned, the note A is in effect repeated. The classic case of virtual repeated notes is that of a trill; it does not seem to be widely recognised that a trill is best played near the keybed. Now a trill involves the alternation of finger movements, and this is the very topic that was discussed in Sec.9.5, where it was explained that the fingers were quite limited when working alternately. Thus, we have two good reasons for playing a trill with small movements near the keybed: firstly, the piano mechanism has limitations; secondly, the fingers have limitations.

9.17 UNORTHODOX MOVEMENTS

Ortmann explains that a pressure transfer technique cannot be used in a trill, for the fatuous reason that when a gradually accelerating trill is executed on a pressure-sensitive plate instead of the piano, the recorded pressure steadily falls. (He is neglecting the inertia of the keys and Newton's second law of motion). Most writers seem to regard a trill as a special case of a finger passage and assume that whatever technique deals with finger passages must deal equally well with a trill. Now pressure transfer techniques can be used to play a precise trill, but, due to the limitations of alternating fingers, such a trill cannot be played very quickly.

Writers in general take the view that the keys should invariably be depressed by the usual finger or arm actions and that depressing the keys by any other means is, somehow, unscientific. It is possible, however, to resort to all kinds of unconventional movements, and such movements are, very often, the only solution to the problem of playing a rapid trill. To illustrate, an unorthodox strategy of my own is now described. This is suitable for a trill in which the thumb is on a white key and the third digit is on the adjacent black key towards the outer side of the hand. The hand is totally locked, with the fingers, hand and wrist rigid, and the arm is in a self-supported condition with the forearm almost horizontal at about 45 degrees to the line of the keys (Fig.9.17.1). In this position, an oscillatory twisting movement of the forearm causes the two digits to execute a sweeping movement across the keys, which produces a trill. Because of the overall rigidity and the strength available in twisting the forearm, very powerful and rapid trills can be produced by this method.

This is just one example of how fingers can be used as passive components in unorthodox movements. There are wide possibilities for this sort of technique.

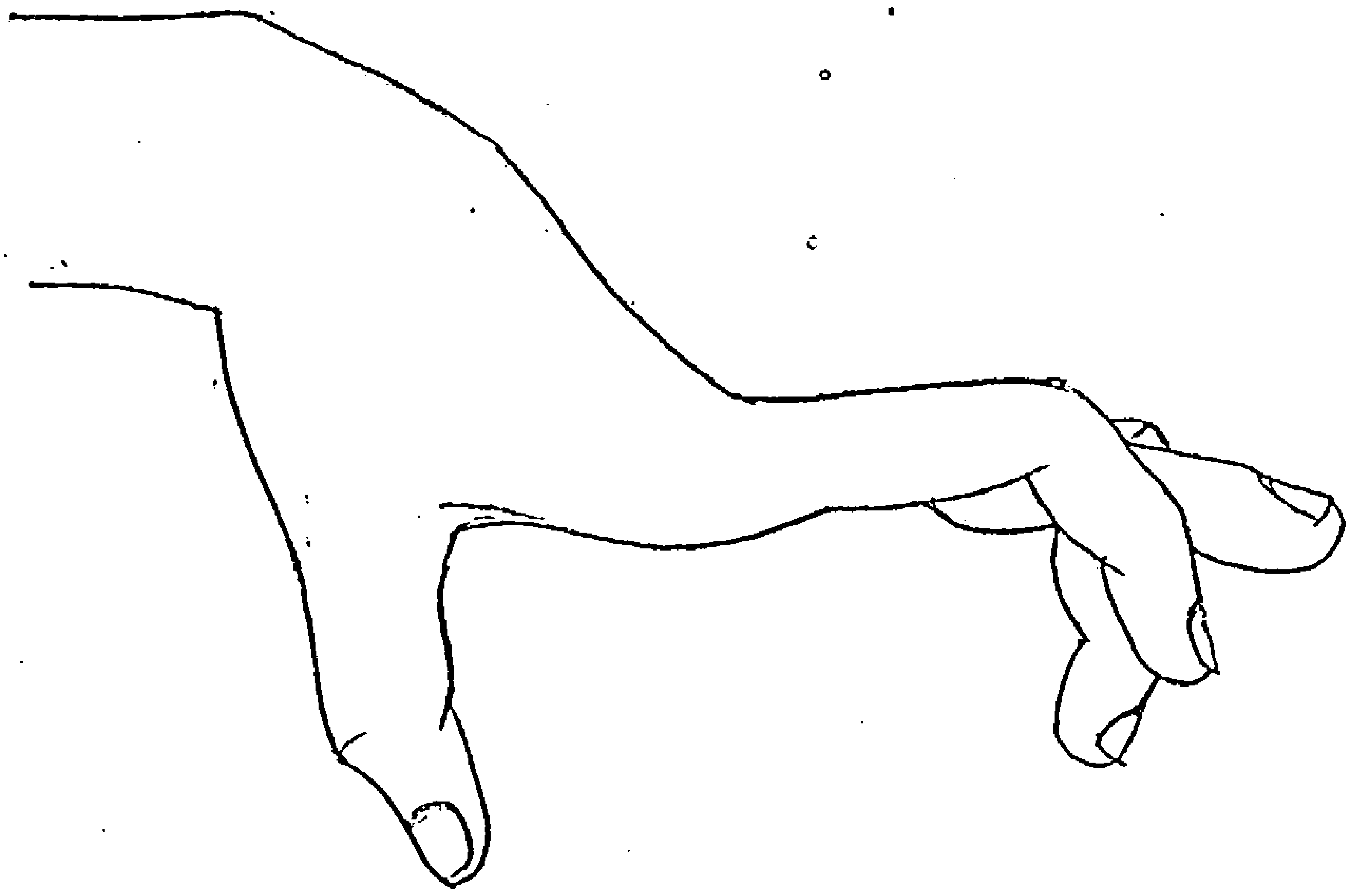


Fig. 9.17.1

9.18 CONTROL BY FRICTION

It should be obvious to any scientist that between the fingertip and the key there is present a fair degree of friction. Not unexpectedly, this friction is often of great importance. However, none of the writers reviewed here has considered friction worthy of any significant comment.

In fact, friction can be regarded in two ways: as a desirable thing, and as an undesirable thing. Let us start with the former case. There is no reason why friction should not be put to use to give added control where problems of lateral stability occur. Obviously, if a sharp lateral deceleration is needed, then, the more friction is available, the more reliably that deceleration can be carried out. In order to increase the friction between finger and key, there should be as much surface area as possible in contact between them. This means, for example, that leaps on to black keys should arrive at a low angle - a conclusion which reinforces that of Sec.9.12.

Considering now the undesirable qualities of friction, it is clearly sometimes advantageous to reduce the friction between finger and key. This would be the case, for instance, in a trill where the technique of the locked hand (Sec.9.17) is being used, because this technique involves a broad sweeping movement of the fingertip across the key surface, and any impedance due to friction is detrimental. The friction can be greatly reduced by curling both fingers right over until only the fingernails come into contact with the keys; as the fingernails are hard and smooth, there is little to upset the movement across the key surface.

The subject of friction has been given only a brief mention here, but it is obviously a factor which cannot be ignored. A full analysis is difficult, because although the value of friction between the fingernail and the key is approximately constant, that between the flesh and the key is subject to far more variation - a nervous pianist performing in public will find his hands perspiring more than usual and this will cause a sharp alteration in the degree of friction present.

9.19 ONE LAST PROBLEM

Most of the problems of piano playing have now been considered, but there is one important point left, which is: when any pianissimo passage is being played, whether it is a finger passage or a set of octaves or chords, in what state of firmness should the fingers be? Ching says that for pianissimo, the fingers should be very relaxed i.e. there should be virtually no stiffness in them due to antagonistic contraction, though his reason is simply that there does not seem to be any advantage in keeping them stiff. Fielden is of the opinion that the greatest control can be achieved when playing quietly by using a great deal of stiffness, in order to avoid any slackness which might cause a bump.

Now this point is very important, but it is not answered here, because common sense will not provide an answer, and the situation is almost impossible to model, due, of course, to the difficulty of representing the structure and properties of the tissues of the hand, which have a vital bearing on the solution.

9.20 SUMMARY

In this chapter we have seen that there is no simple way of executing finger passages because a high degree of standardisation is impossible. The best overall strategy for finger passages seems to be to use Rollbewegung where power or stamina is needed and to use rotational pressure transfer for everything else - both these techniques are pressure transfer techniques and therefore keybedding must be carried out. Arm pressure should range from heavy, for loud passages, to virtually nil, for extremely quiet passages (this last condition is very nearly the same as the self-supported arm, the difference being that with rotational pressure transfer, at a pianissimo level, the hand is not held firmly, i.e. the wrist is relaxed). Finger action should in general be kept to a minimum - there seems no reason to raise the fingers above the keys either for power or staccato or variations in tone quality. The shape of the fingers should normally be well curved, but if Rollbewegung is used they should be almost straight. There seems to be no advantage in altering the height of the wrist from that of its normal position (just above the key-surface), the one exception being for Rollbewegung, which demands a fairly high wrist. As in Chap.7, no use for the upper arm has been found, save the obvious one of moving the elbow around when necessary (for example, when playing at the extremities of the keyboard). No special strategy for pianissimo playing has been found. A new technique for staccato has been proposed. Scales and arpeggios have been discussed. Fielden's theory of nervous control has been singled out for praise. New theories of lateral stability, repeated note structures and control by friction have been put forward and their importance stressed. Finally, mention has been made of the possibility of using quite unorthodox movements involving the use of passive components.

9.21 IN CONCLUSION

Most of the criticism in this chapter has been directed at Ching. This really is a compliment to Ching, because it shows that he makes himself clear enough to be understood, which is more than can be said for the other writers. With Ching, one can at least argue intelligently.

10

THE ROLE OF TECHNICAL KNOWLEDGE IN PIANO PLAYING

10.0 INTRODUCTION

It should be clear by now that the movements involved in piano playing are both varied and complex. It is also obvious that, in order to understand all these movements objectively, a great deal of intellectual effort is needed. Indeed, we can feel quite certain that nobody has ever understood them completely. This being so, one might be tempted to ask the following question: Is it really necessary to understand them objectively? After all, even babies learn to walk without too much trouble - the brain is obviously equipped with highly efficient learning circuitry, so is it not better to leave all the analysis of movement to the brain?

This question can be answered as follows. In the first place, walking is a natural activity, and it seems likely that much information is already "wired-up" at birth. (A deer has to learn to run on the day it is born). Piano playing is by no means a natural activity, and the key mechanism has no "natural" feel to it. In the second place, observation shows that human gait varies a great deal between individuals, which suggests that there is a great deal of leeway in choosing an efficient walking strategy, in other words, a highly suboptimal strategy is still quite acceptable. Now, in playing the works of the great composers on the piano, one is constantly obliged to produce movements which are very close to the optimum,* and which must, therefore, be learned precisely.

But our question can only be answered with certainty if we take a closer look at the learning process. It was explained in Chap.1 that it is necessary for a pianist to analyse the sounds he produces and to try to decide if his arm actions are at fault. Let us go through the process step by step, supposing the pianist to be preparing a piece rather than performing it.

Firstly, the pianist listens to the sounds he makes and compares them to the sounds (in his imagination) that he wanted to produce. Either these sounds coincide to within the tolerance level he has set himself, or they do not. If they do not, then either the piano is faulty, or a mental slip has occurred, or an incorrect arm action has been chosen. If it is decided that an incorrect arm action has been chosen, then the pianist must repeat the section of music which was faulty, but modifying his arm action. Either he adopts an intellectual approach to technique, or he does not. If he does not, then he has no idea of how his arm action should be modified. He must simply try again and again until, hopefully, he plays the section correctly. The process constitutes a random search. If on the other hand, he adopts an intellectual approach, he should have some idea of what is wrong. For example, if he is attempting to play a close-packed sequence of notes at fairly low amplitude and with great evenness, and if he has decided to use a strategy of, say, keeping his hand

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* Relatively speaking

horizontal and transferring the pressure of his arm, then if the result is uneven he must immediately suspect that something is impeding the correct transference of pressure. Basically the decision he must then make is whether he is using an incorrect strategy, or whether he is using a correct strategy but incorrectly applying it. In the first case he must select a new strategy; in the second case he must adjust his actions so they correspond correctly to his chosen strategy. In either case the process constitutes a directed search, analogous to "hill-climbing" methods in optimisation techniques, which is obviously more efficient than a random search.

Assume that the pianist finally hits on the right combination of arm movements, although, in fact, for movements requiring a great deal of skill, he may never do this using a random search. Then in order to benefit from his experience, he must commit to memory the action just performed, otherwise all is lost. Now this is no mean task, for it entails making a record in one's memory each time a movement is made of the position and velocity of every segment in the arm and the force applied by each muscle. The first difficulty is that it is not easy to judge precisely positions and forces within the body - this feedback to the brain is not very accurate. The second difficulty is, it is hard to form a precise memory image of this information. Now, whether an intellectual approach is adopted or not, the difficulties still exist, but, at least, if one has a clear visualisation of strategies then the difficulties are reduced.

Mention was made in the Introduction of a book by Bonpensiere. This book is radically different from all others on piano technique in that it concentrates entirely on the development of learning circuits within the brain. The book is very good as far as it goes, but Bonpensiere seems to be suggesting that all knowledge of biomechanics and piano action is useless, not to say harmful. However, this section has shown, it is hoped, that an intellectual approach has two great advantages : firstly, it enables one to arrive at correct movements more quickly; secondly, it makes it easier to remember these movements.

10.1 A SCHEME FOR MORE EFFICIENT LEARNING

We have seen that an objective intellectual approach to the development of skill is the most efficient approach. The question now is : How can one turn what is known objectively into what is known subconsciously? One of the chief difficulties which has always existed in the past has been the lack of appropriate feedback, as we have just seen. However, in this electronic age, feedback is rarely a problem. A scheme is now presented for a more efficient approach to the learning process.

Firstly, the solutions to all technical problems must be worked out, on the lines of this thesis, (it will be some time before this is achieved). When this information has been obtained, it is presented in analytic form to a computer, which is going to be in charge of operations. Next, the aspiring pianist is thoroughly measured up - the lengths of all his arm segments, the passive properties of his muscles, and so on - and this information is fed to the computer in the form of data. Then the pianist is to sit at a console and tell the computer of his choice of movement (for example, "Today I would like to study the basic action of octave-playing"). After this, he slowly moves his arm in what he imagines to be the correct movement, whilst positional details of his movement are passed to the computer via photoelectric circuits. The computer can then respond with details of how the movement can be improved, taking into account the pianist's own characteristics. It is up to the pianist to form a memory image of this movement.

So much for the kinematics of the movement. The next stage is to set up the correct muscular forces in the pianist's arm. To do this the pianist holds his arm stationary against a clamp in the initial position of the movement, as prescribed by the computer, and flexes his muscles as he thinks appropriate. Details of the muscular activity in his arm are measured by EMG techniques. (One hopes that the present rather barbaric method of measurement is replaced by something more civilised in the future). This data is passed to the computer, which responds as before, guiding the pianist to the correct condition.

Finally the two situations are combined, the tensed muscles giving rise to a movement at full speed. Again the computer monitors the result.

The difficulties in setting up such a "Music laboratory" should not be very great. Programming the computer would only involve straightforward on-line programs, and a small computer could deal with several pianists simultaneously.

The advantages of this scheme are that, firstly, many of the hill-climbing search techniques are done by the computer and, secondly, that good feedback of kinematics and dynamics of the arm is provided. Thus, visualising the process as an adaptive control system, one set of loops (the feedback just mentioned) has been strengthened, and many other loops (of the hill-climbing search variety) have become redundant. This may only seem a small advantage, and so it is, but after all, if a process is improved in efficiency from 0.001% to 0.002%, then what took twenty years can now be done in ten, and it is in this light that the scheme should be judged.

10.2 MODIFICATIONS TO THE PIANO

Over the last hundred years or so, little modification has been made to the basic design of the piano, presumably because until comparatively recently technology has been unable to provide any appreciable improvements. But now with the recent rapid growth in technology, particularly in electronics, we are in a position to radically redesign the piano. The question is : which properties of the instrument are desirable and which are undesirable? Looking back through this thesis we can see that one feature of the piano which might be considered undesirable is that of the noise of the action. It seems quite likely that modern shock-absorbing methods could be used to greatly reduce this, or, as some writers (notably Gat) think that noise is bound up with desirable qualities of sound, these noises could be modified at will.

Another feature of the piano, this time definitely undesirable, is the amount of friction in the action, which is very much dependent on atmospheric conditions (because so much of the action is made of wood). No doubt modern low-friction bearings (possibly PTFE) could be used to advantage.

A further point is that adjustable dampers might be very advantageous. Reference to the diagram of a Bechstein piano in Sec.6.1 shows that the damper operates almost as soon as the key is depressed, and thus a rapid staccato is not really possible. Now if the gap between the end of the key and the bottom of the damper were increased (by deliberate adjustment) then a rapid staccato would be more feasible. A pianist would have to work harder to get a good legato, but at least he would have the opportunity to produce a wider range of textures.

However, by far the most undesirable feature of the present-day pianoforte is that all keyboards are of a uniform size. Thus we have the ludicrous situation that, although a person might be a potential pianistic genius, this person's hands must be big enough to fit the standard keyboard, otherwise he or she stands no chance of being able to play well. Clearly, if someone cannot stretch an octave, then practically every major work written for the piano will prove impossible to play properly. A more subtle point however is that, if a person has hands which can stretch an octave but no more, then, in playing octaves, the fifth finger will have to be splayed out in an almost horizontal position. We have seen that in this position, the finger is at a great structural disadvantage. This disadvantage is magnified by the fact that the fifth finger, although not the weakest finger muscularly, is by far the weakest finger structurally (a point not realised by other writers). The outcome of this is that for someone with small hands, most of the strength available for playing octaves simply cannot be applied. In this respect, women, as a race, being equipped by Nature with appreciably smaller hands, are very much discriminated against by the makers of pianos. Strength in playing, as far as women are concerned, lies not in having powerful biceps but in being born with abnormally large hands. (Nobody seems to have pointed this out). This is why the number of first class women pianists who can play powerfully is virtually nil. About the turn of the century, a Professor Zabludowski (quoted by Breithaupt) put forward the suggestion that a smaller keyboard should be provided as an alternative to the conventional one, and his suggestion is endorsed by Breithaupt. Perhaps with the emergence of the newly-liberated woman this will at last come about. It is interesting to note that the great pianist Josef Hofmann had very small hands and had to resort to commissioning a special piano for himself with a smaller keyboard (Schonberg, 1964).

Another undesirable feature of the piano is the fact that, as slight differences in force become so important at low amplitudes, it is inevitable that the minimum force needed to produce a note will vary from key to key. Thus if a pianist wants to play with absolute evenness at a very low amplitude, he must remember the individual resistance of every key, and somehow compensate his strategies to allow for any differences. One can unhesitatingly say, therefore, that if all the resources of modern technology were brought to bear on the problem of making the actions of the keys as similar as possible, few pianists would grumble.

But why stop there? The whole mechanism of the piano could be replaced by electrical circuitry, which could be arranged to give virtually any refinement. The amplitude versus force curve could be straightened out, which would make quiet playing simple and would remove the problem of stamina. Differences in tone quality could be built into the circuitry, to be brought into play at the flick of a switch (preferably a foot-operated "touch-switch"). For that matter, controls could be introduced to adjust groups of notes, so that evenness in amplitude and frequency would be automatically brought about.

However, at this point we must take stock of what we want from the piano. There is a danger in making things too easy. The Olympic Games would not be improved by equipping the athletes with roller skates, nor would Wimbledon be a greater spectacle if the nets were lowered for the convenience of the players. On the other hand few people object to letting competitors at these events choose shoes that fit or rackets that have unbroken strings. The idea of "improving" the piano is analogous to this. Minor adjustments, aimed simply at producing a good quality piano are eminently worthwhile, but any alteration of the basic mechanism of the piano must ultimately defeat its own end, for the music produced by such a "simplified" instrument would not be as satisfactory as that produced by an old-fashioned "difficult" one. This is a subtle and complex point and one that belongs to aesthetics, but suffice it to say here that many of the great composers (notably Beethoven, Chopin, Liszt and Rachmaninoff) were also superb pianists and their music is written in such a way that the aesthetic content is a function of the keyboard structure. Thus, for example, a rather exotic harmony needs a rather exotic twist of the hands, a powerful passage needs a lot of muscular power, a delicate passage needs great physical delicacy, and so on.

Whether these points are of value to an audience is not easy to say, but for the real pianist there can be no doubt that the instrument that was good enough for the great composers is good enough for him.

11

CONCLUSIONS

First, let it be said that the title of this thesis was chosen carefully. It is quite impossible to give a comprehensive coverage of piano technique in one thesis, and in this work many technical problems have been given only a brief airing. The study of arpeggio-playing in particular is a subject in itself, and the treatment given to it here is woefully inadequate (though no-one else seems to have much idea on how to play arpeggios). Furthermore, in every chapter the discussion has had to be cut short in order to meet the time limitations of a doctoral thesis. A policy could have been adopted of relentlessly pursuing one aspect of piano playing in something of an optimal fashion; however, in view of the current state of the art, a set of basic investigations into a selection of topics - which is the course taken here - is a fair strategy.

The computer programs in this thesis have not proved anything new, but they demonstrate that computer simulation of piano playing is a workable proposition. The discussions in this thesis are at a higher scientific level than that of the authors listed in Chap.0. To put their work in perspective let it be said that the two most scientific writers, namely Ortmann and Ching, never go beyond the level of very simple equations - about " $y = x^2$ " standard.

What this thesis has not succeeded in doing is discovering the ultimate method of playing the piano. But at least it has succeeded in showing that, in biomechanics and particularly in the mechanics of playing the piano, a little knowledge can be a dangerous thing.

APPENDIX 1

SOME DETAILS OF THE COMPUTER PROGRAMMING

A1.1 CHOICE OF METHOD

In carrying out simulations, one has the choice of using several computing techniques, for example, analogue computation, hybrid computation, digital computation using a high level language such as Fortran, or digital computation using a simulation language. For very simple arm models it matters little which of these methods is used; the relative merits of each one are too well known to need repeating here. As the models become complicated, however, various factors begin to assert themselves. For instance, with both analogue and hybrid computation, it is difficult to multiply variables satisfactorily; most analogue and hybrid computers have relatively few multiplying units, and these are not blessed with great accuracy. Now in constructing multilink arm models, an unusually large quantity of moment terms appears, and this places a strain on multiplying resources. As for digital computer methods, everything depends on which computer languages are available. Simple simulation languages are useful in dealing with integration, but generally speaking the amount of computer time taken can be rather discouraging; furthermore, the model of the piano key mechanism presented in this thesis needs a fairly sophisticated switching technique in simulation, and it is doubtful if many simulation languages could deal with this efficiently. Programming with Fortran has none of the disadvantages mentioned so far, but integration can be a great problem. As it happens, at Salford University there is generally available a powerful and versatile integration "package" written by J.L. Hay of the Dept. of Electrical Engineering. Because of this, Fortran programming was used for all the simulations in this thesis. To sum up: Fortran was used because with Fortran, (1) there would be no difficulty with multiplication if more complex arm models were developed, (2) computing time is much less than with many simulation languages (some of the arm movements of Chap.4 took around 5 mins. to compute, even in Fortran), (3) switching presents no difficulty, (4) an integration package is available.

A1.2 THE INTEGRATION PACKAGE

Full details of this package can be found in various internal publications of Salford University. Briefly, the user can operate the integration routine by making a call from his program, giving the values of five parameters. Only one statement need be made for a complete integration, as this statement automatically unloads the routine from the computer library. Such details as absolute error, relative error and step length are specified by the user, and there is a choice of three different types of integration (Euler, Euler-Schiesser and Runge-Kutta-Merson). In using the routine, the programmer must supply two subroutines; the first, "DERIV", must contain the differential equations of the system, arranged in canonic state variable form; the second, "CNTRL", is for controlling the integration routine, and it continually tests the terminating and switching conditions laid down by the user. It is more efficient to use two subroutines, rather than one, because DERIV is used freely by the integration routine, whereas CNTRL is entered only at times specified by the user (say, at the end of each integration step).

A1.3 SOME NOTES ON INDIVIDUAL PROGRAMS

The programs of Chap.4 are reasonably straightforward. The switching is done in CNTRL by changing the values of parameters when the variable t has reached specified amounts.

The piano key simulation (Program 6) needs careful switching. It is best to construct a general program which will deal with all possible ways of depressing the key. Accordingly, in this program, CNTRL contains several tests and combinations of tests to determine the phase of the mechanism, represented by the program variable IPHASE. For example, the combination: $\phi_k \geqslant \phi_{kb}$ and $\phi_h \ngeqslant \phi_{hs}$ shows that phase 2 has ended, and the combination: $\phi_k < \phi_{kb}$ and $\dot{\phi}_k \leqslant 0$ shows that the key has failed to reach the bed and phase 3 has begun. The variable IPHASE is used in DERIV to decide which set of differential equations shall be used, and it controls the flow of the program through CNTRL itself.

The arm/key simulation (Program 7) consists of the main part of the Chap.4 simulations dovetailed with Program 6.

APPENDIX 2

STANDARD VALUES

The following values are the eventual ones used for the simulations :-

F^M = 1600 N
μ = 1940 Ns/m
K = 22400 N/m
I = 0.06 kg.m^2
p_0 = 0.35 m
p_1 = 0.04 m
p_2 = 0.04 m
l = 0.42 m

In addition the values given in Sec.6.1.1 were used.

GLOSSARY OF MUSICAL TERMS

This is not a complete glossary; it contains just enough to be able to decipher most of the musical examples of Chap.1.

A "third" is a space bridging three notes inclusively, e.g. from C to E; an "octave" bridges eight notes, and so on. When the names of notes are written, a' is one octave above A (which is a tenth below middle C), A' is one octave below, a" is two octaves above, and so on. In a musical score, the pitch of a note is indicated by the "stave" i.e. five horizontal lines. If the stave is marked "𝄞" the pitches of each line are, reading upwards, e', g', b", d", f".If it is marked"𝄢", the pitches are, reading downwards, a', F, D, B, G'. The spaces between the lines indicate the pitches which lie between those which are indicated by the lines. Notes lying outside the range of the staves are indicated by short vertical extensions of the staves. The duration of a note is indicated by its colour (black or white) or the number of tails on its stem: 𝅝, 𝅗𝅥, ♩, ♪, 𝅘𝅥𝅯 (semibreve, minim, crotchet, quaver, semiquaver) indicate a sequence of notes whose duration is progressively halved. Durations can be summed by connecting notes with "‿". A dot after a note indicates that the duration is 50% longer. For convenience, tails are often gathered into groups. If such a group is marked with a number, then this indicates a different proportionate length e.g.  takes up the same time as ♩ Pitch can be modified by the sign "♯" (sharp) which raises the note by one semitone, or "♭" (flat) which lowers it by one semitone, both signs being placed immediately in front of a note. If these signs appear at the beginning of a stave, this means that all notes following them are modified as the signs indicate, unless it is stated otherwise. The sign " ♮ " (natural) is used for stating otherwise and means "neither sharp nor flat". The sign "8------" over a note(s) indicates that the note(s) is to be played one octave higher than shown. Notes written in vertical coincidence are to be played simultaneously. Vertical lines ("bar lines") are used to indicate regular points in time. Tempo is indicated by such signs as ♩ = 60 which means that there are 60 crotchets per minute. Other instructions are usually written in Italian; "f" stands for "forte" (loud), "ff" for "fortissimo" and so on. "Tr∿∿∿" written over a note means that there is a trill between that note and the next one either a tone or a semitone up. (If there is any doubt as to which is the other note, then a sharp, flat or natural sign is shown).

APPENDIX 4

LITERATURE SEARCH

It will be appreciated that searching the literature under titles such as "arm", "muscle" and "biomechanics" leads to an embarrassment of reading matter. For this reason research into biomechanics was done intuitively. It soon becomes clear that Wilkie's article (1950) is the central one in the field, and no significant modification of his results seems to exist.

The main area of research in this thesis is that of piano playing. Therefore a thorough search was carried out to find which books had been written on the subject. The major catalogues of books published in the English language from about 1930 were searched. Common sense was used to whittle the titles down to those listed in Chap.0. Confirmation that these are the most important books comes from the fact that their authors had to refer to one another, and to no-one else. In addition to this search, catalogues of most of the theses published in English since about 1950 were studied; nothing relevant was found.

APPENDIX 5

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APPENDIX 6

COMMON SYMBOLS

For convenience, here are listed some of the more commonly used symbols :-

Variables

F	Force in muscle
F^M	Maximum force of muscle
g	Acceleration of gravity
I	Moment of inertia
l	Length of arm link
m	Mass
p	Lever arm of muscle
t	Time
W	Force applied to key
x_f	Lever arm of key
ζ	Stimulation of muscle
θ	Angular displacement of arm link
κ	Elasticity of SEM
μ	Viscosity of SEM
λ	Length of SEM
ϕ	Angular displacement of piano link
ψ	Angle between muscle and arm link

Suffices

o	Initial value
b	Keybed
e	Point of escapement
h	Hammer
i	Number of arm link
j	Number of muscle
k	Key
p	Whole key mechanism
s	String

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